

CHAPTER 1—PROBLEM SOLUTIONS

1.1 (a) $I = \frac{V}{R} = \frac{10 \text{ V}}{1 \text{ k}\Omega} = 10 \text{ mA}$

(b) $R = \frac{V}{I} = \frac{10 \text{ V}}{1 \text{ mA}} = 10 \text{ k}\Omega$

(c) $V = IR = 10 \text{ mA} \times 10 \text{ k}\Omega = 100 \text{ V}$

(d) $I = \frac{V}{R} = \frac{10 \text{ V}}{100 \text{ }\Omega} = 0.1 \text{ A}$

Note: Volts, milliamps, and kilo-ohms constitute a consistent set of units.

1.2 (a) $P = I^2 R = (30 \times 10^{-3})^2 \times 1 \times 10^3 = 0.9 \text{ W}$

Thus, R should have a 1-W rating.

(b) $P = I^2 R = (40 \times 10^{-3})^2 \times 1 \times 10^3 = 1.6 \text{ W}$

Thus, the resistor should have a 2-W rating.

(c) $P = I^2 R = (3 \times 10^{-3})^2 \times 10 \times 10^3 = 0.09 \text{ W}$

Thus, the resistor should have a $\frac{1}{8}$ -W rating.

(d) $P = I^2 R = (4 \times 10^{-3})^2 \times 10 \times 10^3 = 0.16 \text{ W}$

Thus, the resistor should have a $\frac{1}{4}$ -W rating.

(e) $P = V^2/R = 20^2/(1 \times 10^3) = 0.4 \text{ W}$

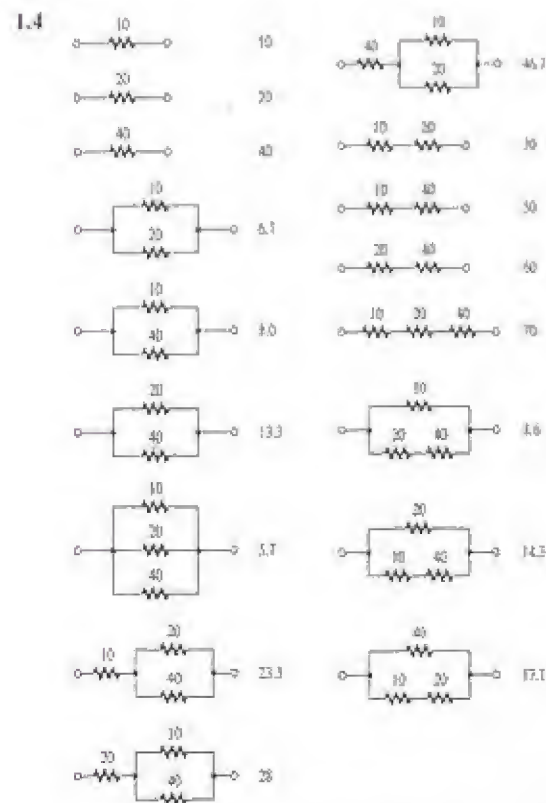
Thus, the resistor should have a $\frac{1}{2}$ -W rating.

(f) $P = V^2/R = 11^2/(1 \times 10^3) = 0.121 \text{ W}$

Thus, a rating of $\frac{1}{4}$ W should theoretically suffice though $\frac{1}{2}$ W would be prudent to allow for consistent tolerances and measurement errors.

- 1.3 (a) $V = IR = 10 \text{ mA} \times 1 \text{ k}\Omega = 10 \text{ V}$
 $P = I^2 R = (10 \text{ mA})^2 \times 1 \text{ k}\Omega = 100 \text{ mW}$
 (b) $R = V/I = 10 \text{ V}/1 \text{ mA} = 10 \text{ k}\Omega$
 $P = VI = 10 \text{ V} \times 1 \text{ mA} = 10 \text{ mW}$
 (c) $I = P/V = 1 \text{ W}/10 \text{ V} = 0.1 \text{ A}$
 $R = V/I = 10 \text{ V}/0.1 \text{ A} = 100 \Omega$
 (d) $V = P/I = 0.1 \text{ W}/10 \text{ mA} = 100 \text{ mW}/10 \text{ mA} = 10 \text{ V}$
 $R = V/I = 10 \text{ V}/10 \text{ mA} = 1 \text{ k}\Omega$
 (e) $P = I^2 R \Rightarrow I = \sqrt{P/R}$
 $I = \sqrt{1000 \text{ mW}/1 \text{ k}\Omega} = 31.6 \text{ mA}$
 $V = IR = 31.6 \text{ mA} \times 1 \text{ k}\Omega = 31.6 \text{ V}$

Note: V, mA, k Ω , and mW constitute a consistent set of units.



Thus, there are 17 possible resistance values.

1.5 Shunting the $10 \text{ k}\Omega$ by a resistor of value R result in the combination having a resistance R_{eq} ,

$$R_{eq} = \frac{10R}{R + 10}$$

Thus, for a 1% reduction,

$$\frac{R}{R + 10} = 0.99 \Rightarrow R = 990 \text{ k}\Omega$$

For a 5% reduction,

$$\frac{R}{R + 10} = 0.95 \Rightarrow R = 190 \text{ k}\Omega$$

For a 10% reduction,

$$\frac{R}{R + 10} = 0.90 \Rightarrow R = 90 \text{ k}\Omega$$

For a 50% reduction,

$$\frac{R}{R + 10} = 0.50 \Rightarrow R = 10 \text{ k}\Omega$$

Shunting the $10 \text{ k}\Omega$ by

(a) $1 \text{ M}\Omega$ result in

$$R_{eq} = \frac{10 \times 1000}{1000 + 10} = \frac{10}{1.01} = 9.9 \text{ k}\Omega, \text{ a 1\% reduction;}$$

(b) $100 \text{ k}\Omega$ results in

$$R_{eq} = \frac{10 \times 100}{100 + 10} = \frac{10}{1.1} = 9.09 \text{ k}\Omega, \text{ a 9.1\% reduction;}$$

(c) $10 \text{ k}\Omega$ results in

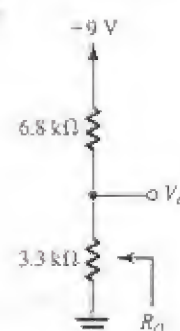
$$R_{eq} = \frac{10}{10 + 10} = 5 \text{ k}\Omega, \text{ a 50\% reduction.}$$

1.6 $V_O = V_{DD} \frac{R_2}{R_1 + R_2}$

To find R_D , we short circuit V_{DD} and look back into node X,

$$R_D = R_2 \parallel R_1 = \frac{R_1 R_2}{R_1 + R_2}$$

1.7



$$V_o = 9 \frac{3.3}{3.3 + 6.8}$$

$$= 2.94 \text{ V}$$

$$R_o = 2.22 \text{ k}\Omega$$

For $\pm 5\%$ resistor tolerance the extreme values of V_o are

$$V_{o, \text{low}} = 9 \frac{3.3(1 - 0.05)}{3.3(1 - 0.05) + 6.8(1 + 0.05)} \\ = 2.75 \text{ V}$$

$$V_{o, \text{high}} = 9 \frac{3.3(1 + 0.05)}{3(1 + 0.05) + 6.8(1 - 0.05)}$$

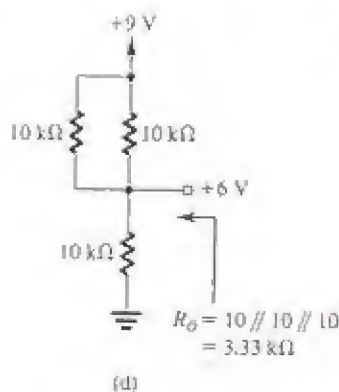
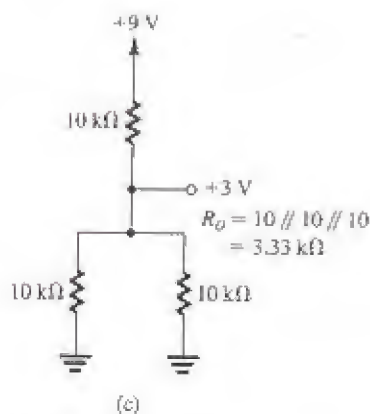
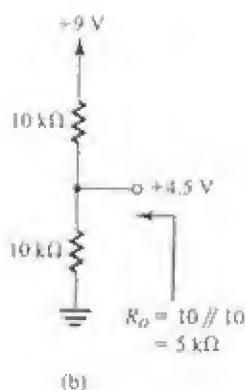
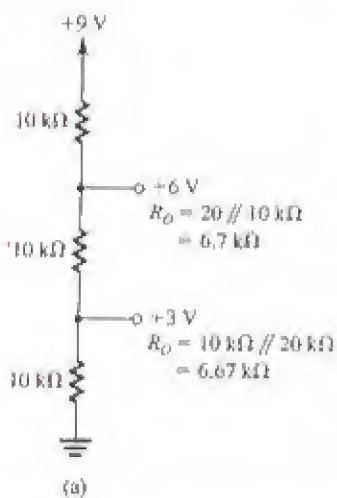
$$= 3.14 \text{ V}$$

The extreme values of R_o are

$$R_{o, \text{low}} = \frac{3.3(1 - 0.05) \times 6.8(1 - 0.05)}{3.3(1 - 0.05) + 6.8(1 - 0.05)} \\ = 2.22(1 - 0.05) = 2.11 \text{ k}\Omega$$

$$R_{o, \text{high}} = 2.22(1 + 0.05) = 2.33 \text{ k}\Omega$$

1.8

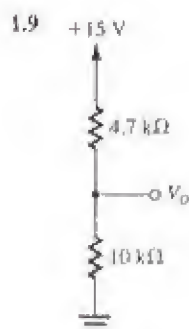


Voltages generated:

+3 V (two ways: (a) and (c) with (c) having lower output resistance)

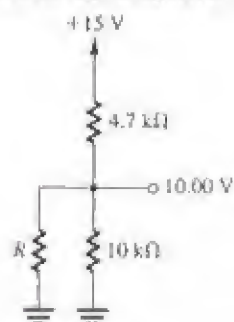
+4.5 V (b)

+6 V (two ways: (a) and (d) with (d) having a lower output resistance)



$$V_O = 15 \frac{10}{10 + 4.7} = 10.2 \text{ V}$$

To reduce V_O to 10.00 V we shunt the 10-kΩ resistor by a resistor R whose value is such that $10 \parallel R = 2 \times 4.7$.



Thus

$$\frac{1}{10} + \frac{1}{R} = \frac{1}{9.4}$$

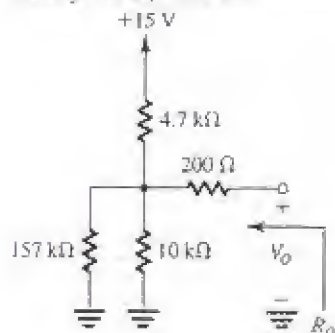
$$\Rightarrow R = 156.7 = 157 \text{ k}\Omega$$

Now,

$$R_O = 10 \text{ k}\Omega \parallel R \parallel 4.7 \text{ k}\Omega$$

$$= 9.4 \parallel 4.7 = \frac{9.4}{2} = 4.7 \text{ k}\Omega$$

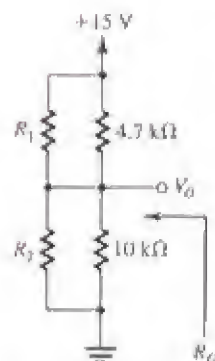
To make $R_O = 3.33$ we add a series resistance of approximately 200 Ω, as shown.



To obtain $V_O = 10.00 \text{ V}$ and $R_O = 3 \text{ k}\Omega$ we have to shunt both the 4.7-kΩ and the 10-kΩ resistors as shown. To yield an output voltage $V_O = 10.00 \text{ V}$ we must have

$$\frac{(R_2 \parallel 10)}{R_2'} = \frac{2(R_1 \parallel 4.7)}{R_1'}$$

$$R_2' = 2R_1' \quad (1)$$



For $R_O = 3 \text{ k}\Omega$ we must have

$$R_1' \parallel R_2' = 3 \quad (2)$$

Solving (1) and (2) yields

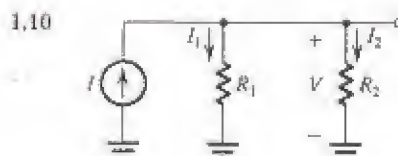
$$R_1' = 4.5 \text{ k}\Omega$$

$$R_2' = 9.0 \text{ k}\Omega$$

which can be used to find R_1 and R_2 respectively,

$$R_1 = 157 \text{ k}\Omega$$

$$R_2 = 90 \text{ k}\Omega$$



$$V = I(R_1 \parallel R_2)$$

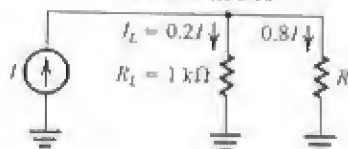
$$= I \frac{R_1 R_2}{R_1 + R_2}$$

$$I_1 = \frac{V}{R_1} = I \frac{R_2}{R_1 + R_2}$$

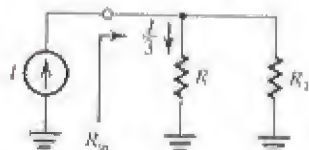
$$I_2 = \frac{V}{R_2} = I \frac{R_1}{R_1 + R_2}$$

1.11 Connect a resistor R in parallel with R_L . To make $I_L = 0.2I$ (and thus the current through R , $0.8I$), R should be such

$$0.2I \times 1 \text{ k}\Omega = 0.8I R \\ \Rightarrow R = 250 \Omega$$



1.12



To make the current through R equal to $I/3$ we shunt R by a resistance R_1 of value such that the current through it will be $2I/3$; thus

$$\frac{I}{3} R = \frac{2I}{3} R_1 \Rightarrow R_1 = \frac{R}{2}$$

The input resistance of the divider, R_{in} , is

$$R_{in} = R \parallel R_1 = R \parallel \frac{R}{2} = \frac{1}{3} R$$

Now if R_1 is 10% too high, i.e.,

$$R_1 = 1.1 \frac{R}{2}$$

the problem can be solved in two ways:

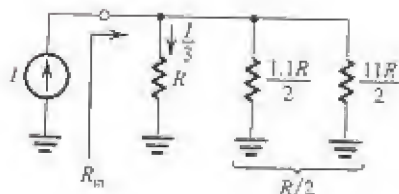
(a) Connect a resistor R_2 across R_1 of value such that $R_1 \parallel R_2 = R/2$, thus

$$\frac{R_2(1.1R/2)}{R_2 + (1.1R/2)} = \frac{R}{2}$$

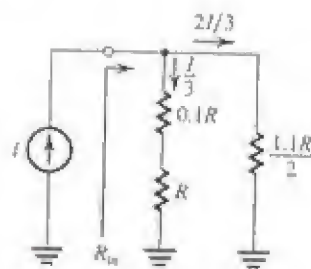
$$1.1R_2 = R_2 + \frac{1.1R}{2}$$

$$\Rightarrow R_2 = \frac{1.1R}{2} = 5.5R$$

$$R_{in} = R \parallel \frac{1.1R}{2} \parallel \frac{1.1R}{2} \\ = R \parallel \frac{R}{2} = \frac{R}{3}$$



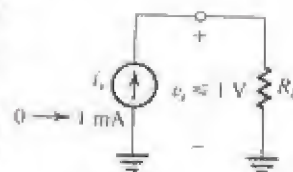
(b) Connect a resistor in series with the load resistor R so as to raise the resistance of the load branch by 10%, thereby restoring the current division ratio to its desired value. The added series resistance must be 10% of R i.e., $0.1R$.



$$R_{in} = 1.1R \parallel \frac{1.1R}{2} \\ = \frac{1.1R}{3}$$

i.e., 10% higher than in case (a).

1.13 If $R_L = 10 \text{ k}\Omega$ then a voltage of 0 to 10 V may develop across the source. To limit the voltage to the specified maximum of 1 V, we have to shunt

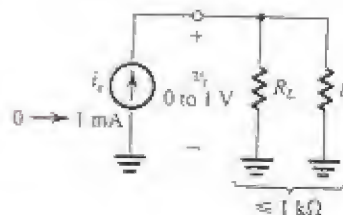


R_L with a resistor R whose value is such that the parallel combination of R_L and R is $\leq 1 \text{ k}\Omega$. Thus,

$$\frac{RR_L}{R + R_L} \leq 1$$

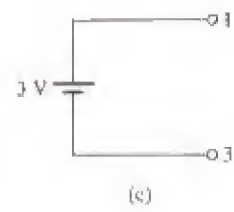
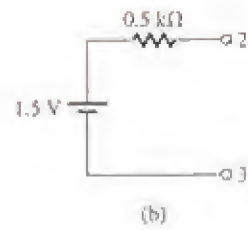
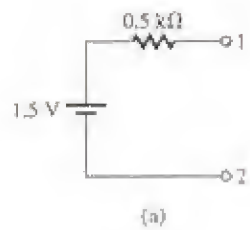
$$R \leq 1.111 \text{ k}\Omega$$

$$\Rightarrow R = 1.1 \text{ k}\Omega$$

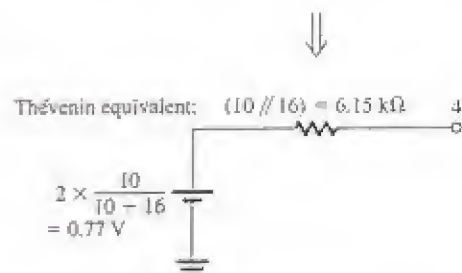
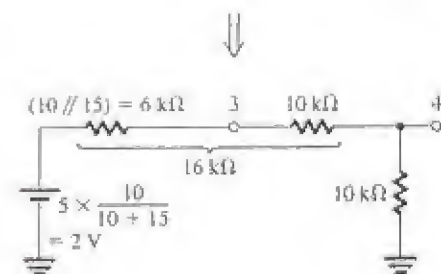
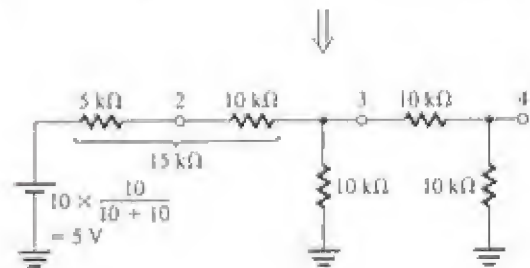
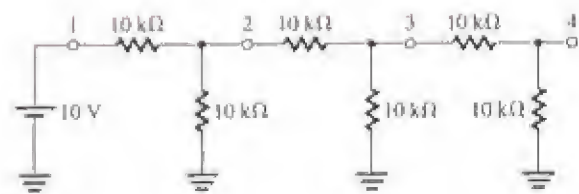


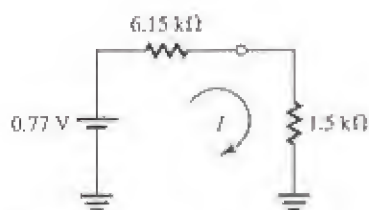
The resulting circuit, utilizing only one additional resistor of value $1.1 \text{ k}\Omega$ creates a current divider across the source.

1.14



1.15





Now, when a resistance of $1.5 \text{ k}\Omega$ is connected between 4 and ground,

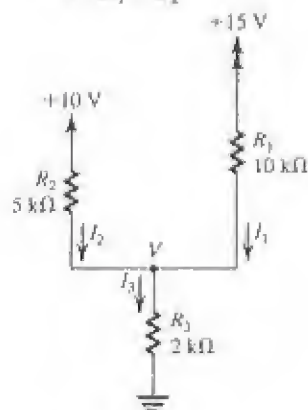
$$I = \frac{0.77}{6.15 + 1.5} = 0.1 \text{ mA}$$

1.16 (a) Node equation at the common node yields

$$I_3 = I_1 + I_2$$

Using the fact that the sum of the voltage drops across R_1 and R_3 equals 15 V , we write

$$\begin{aligned} 15 &= I_1 R_1 + I_3 R_3 \\ &= 10 I_1 + (I_1 + I_2) \times 2 \\ &= 12 I_1 + 2 I_2 \end{aligned}$$



That is,

$$12 I_1 + 2 I_2 = 15 \quad (1)$$

Similarly, the voltage drops across R_2 and R_3 add up to 10 V , thus

$$\begin{aligned} 10 &= I_2 R_2 + I_3 R_3 \\ &= 5 I_2 + (I_1 + I_2) \times 2 \end{aligned}$$

which yields

$$2 I_1 + 7 I_2 = 10 \quad (2)$$

Equations (1) and (2) can be solved together by multiplying (2) by 6,

$$12 I_1 + 42 I_2 = 60 \quad (3)$$

Now, subtracting (1) from (3) yields

$$40 I_2 = 45$$

$$\Rightarrow I_2 = 1.125 \text{ mA}$$

Substituting in (2) gives

$$2 I_1 = 10 - 7 \times 1.125 \text{ mA}$$

$$\Rightarrow I_1 = 1.0625 \text{ mA}$$

$$I_3 = I_1 + I_2$$

$$= 1.0625 + 1.1250$$

$$= 1.1875 \text{ mA}$$

$$V = I_3 R_3$$

$$= 1.1875 \times 2 = 2.3750 \text{ V}$$

To summarize:

$$I_1 \approx 1.06 \text{ mA} \quad I_2 \approx 1.13 \text{ mA}$$

$$I_3 \approx 1.19 \text{ mA} \quad V \approx 2.38 \text{ V}$$

(b) A node equation at the common node can be written in terms of V as

$$\frac{15 - V}{R_1} + \frac{10 - V}{R_2} = \frac{V}{R_3}$$

Thus,

$$\frac{15 - V}{10} + \frac{10 - V}{5} = \frac{V}{2}$$

$$\Rightarrow 0.8V = 3.5$$

$$\Rightarrow V = 2.375 \text{ V}$$

Now, I_1 , I_2 , and I_3 can be easily found as

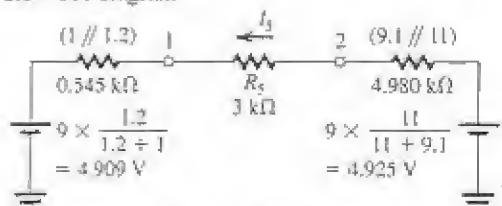
$$I_1 = \frac{15 - V}{10} = \frac{15 - 2.375}{10} = 1.0625 \text{ mA} \approx 1.06 \text{ mA}$$

$$I_2 = \frac{10 - V}{5} = \frac{10 - 2.375}{5} = 1.125 \text{ mA} \approx 1.13 \text{ mA}$$

$$I_3 = \frac{V}{R_3} = \frac{2.375}{2} = 1.1875 \text{ mA} \approx 1.19 \text{ mA}$$

Method (b) is much preferred; faster, more insightful and less prone to errors. In general, one attempts to identify the least possible number of variables and write the corresponding minimum number of equations.

1.17 See diagram

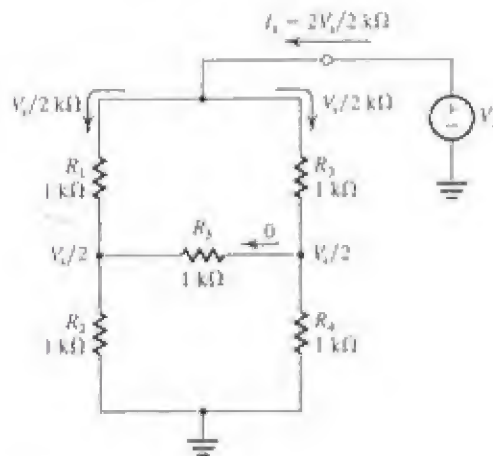


$$I_2 = \frac{4.925 - 4.909}{4.98 + 3 + 0.545} = 1.88 \mu\text{A}$$

$$V_2 = 1.88 \mu\text{A} \times 3 \text{ k}\Omega = 5.64 \text{ mV}$$

1.18 From the symmetry of the circuit, there will be no current in R_3 . (Otherwise the symmetry would be violated.) Thus each branch will carry a current $V_s/2 \text{ k}\Omega$ and I_s will be the sum of the two current.

$$I_s = \frac{2V_s}{2 \text{ k}\Omega} = \frac{V_s}{1 \text{ k}\Omega}$$



Thus,

$$R_{eq} = \frac{V_s}{I_s} = 1 \text{ k}\Omega$$

Now, if R_4 is raised to $1.2 \text{ k}\Omega$ the symmetry will be broken. To find I_s we use Thévenin's theorem as follows:

$$I_s = \frac{0.545V_s - 0.5V_s}{0.5 + 1 + 0.545} = 0.022V_s$$

$$V_1 = \frac{V_s}{2} + 0.022V_s \times 0.5$$

$$= 0.5V_s \times 1.022 = 0.511V_s$$

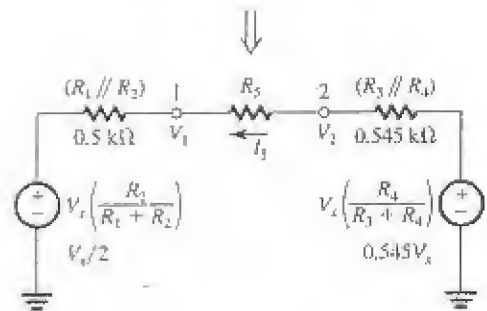
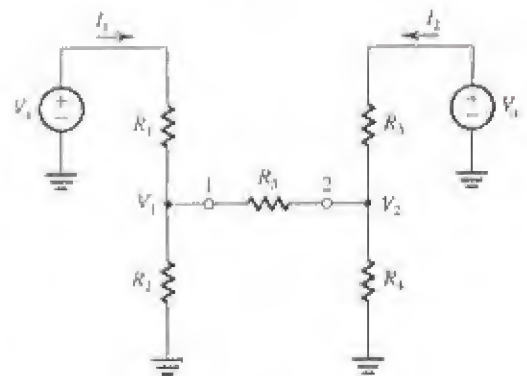
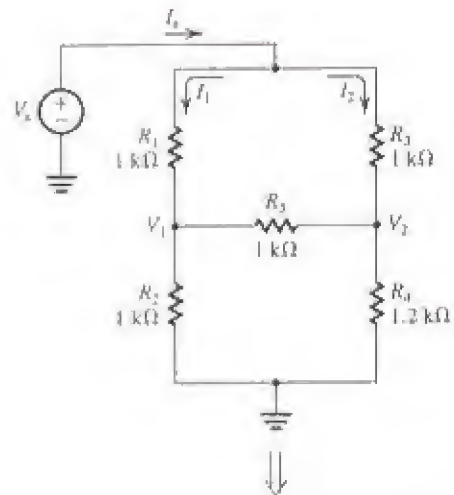
$$V_2 = V_1 + I_s R_3 = 0.533V_s$$

$$I_1 = \frac{V_s - V_1}{1 \text{ k}\Omega} = 0.489V_s$$

$$I_2 = \frac{V_s - V_2}{1 \text{ k}\Omega} = 0.467V_s$$

$$I_s = I_1 + I_2 = 0.956V_s$$

$$\Rightarrow R_{eq} = \frac{V_s}{I_s} = 1.05 \text{ k}\Omega$$



1.19 (a) $T = 10^{-4} \text{ ms} = 10^{-7} \text{ s}$

$$f = \frac{1}{T} = 10^7 \text{ Hz}$$

$$\omega = 2\pi f = 6.28 \times 10^7 \text{ rad/s}$$

(b) $f = 1 \text{ GHz} = 10^9 \text{ Hz}$

$$T = \frac{1}{f} = 10^{-9} \text{ s}$$

$$\omega = 2\pi f = 6.28 \times 10^9 \text{ rad/s}$$

(c) $\omega = 6.28 \times 10^2 \text{ rad/s}$

$$f = \frac{\omega}{2\pi} = 10^2 \text{ Hz}$$

$$T = \frac{1}{f} = 10^{-2} \text{ s}$$

(d) $T = 10 \text{ s}$

$$f = \frac{1}{T} = 10^{-1} \text{ Hz}$$

$$\omega = 2\pi f = 6.28 \times 10^{-1} \text{ rad/s}$$

(e) $f = 60 \text{ Hz}$

$$T = \frac{1}{f} = 1.67 \times 10^{-2} \text{ s}$$

$$\omega = 2\pi f = 3.77 \times 10^2 \text{ rad/s}$$

(f) $\omega = 1 \text{ krad/s} = 10^3 \text{ rad/s}$

$$f = \frac{\omega}{2\pi} = 1.59 \times 10^2 \text{ Hz}$$

$$T = \frac{1}{f} = 6.28 \times 10^{-3} \text{ s}$$

(g) $f = 1900 \text{ MHz} = 1.9 \times 10^9 \text{ Hz}$

$$T = \frac{1}{f} = 0.526 \times 10^{-9} \text{ s}$$

$$\omega = 2\pi f = 1.194 \times 10^9 \text{ rad/s}$$

1.20 (a) $Z = 1 \text{ k}\Omega$ at all frequencies

(b) $Z = 1/j\omega C = -j \frac{1}{2\pi f \times 10 \times 10^{-9}}$

At $f = 60 \text{ Hz}$, $Z = -j265 \text{ k}\Omega$

At $f = 100 \text{ kHz}$, $Z = -j159 \text{ }\Omega$

At $f = 1 \text{ GHz}$, $Z = -j0.016 \text{ }\Omega$

(c) $Z = 1/j\omega C = -j \frac{1}{2\pi f \times 2 \times 10^{-12}}$

At $f = 60 \text{ Hz}$, $Z = -j1.33 \text{ G}\Omega$

At $f = 100 \text{ kHz}$, $Z = -j0.8 \text{ M}\Omega$

At $f = 1 \text{ GHz}$, $Z = -j79.6 \text{ }\Omega$

(d) $Z = j\omega L = j2\pi fL = j2\pi f \times 10 \times 10^{-3}$

At $f = 60 \text{ Hz}$, $Z = j3.77 \text{ }\Omega$

At $f = 100 \text{ kHz}$, $Z = j6.28 \text{ k}\Omega$

At $f = 1 \text{ GHz}$, $Z = j62.8 \text{ M}\Omega$

1.21 (a) $Z = R + \frac{1}{j\omega C}$

$$= 10^3 + \frac{1}{j2\pi \times 10 \times 10^3 \times 10 \times 10^{-9}}$$

$$= (1 - j1.59) \text{ k}\Omega$$

(b) $Y = \frac{1}{R} + j\omega C$

$$= \frac{1}{10^3} + j2\pi \times 10 \times 10^3 \times 0.01 \times 10^{-6}$$

$$= 10^{-3}(1 + j0.628) \text{ S}$$

$$Z = \frac{1}{Y} = \frac{1000}{1 + j0.628}$$

$$= \frac{1000(1 - j0.628)}{1 + 0.628^2}$$

$$= (717.2 - j450.4) \text{ }\Omega$$

(c) $Y = \frac{1}{R} + j\omega C$

$$= \frac{1}{100 \times 10^3} + j2\pi \times 10 \times 10^3 \times 100 \times 10^{-12}$$

$$= 10^{-5}(1 + j0.628)$$

$$Z = \frac{10^5}{1 + j0.628}$$

$$= (71.72 - j45.04) \text{ k}\Omega$$

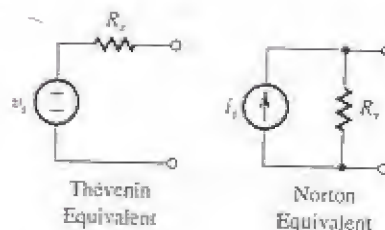
(d) $Z = R + j\omega L$

$$= 100 + j2\pi \times 10 \times 10^3 \times 10 \times 10^{-3}$$

$$= 100 + j6.28 \times 100$$

$$= (100 + j628) \text{ }\Omega$$

1.22



$$\begin{aligned}v_{oc} &= v_s \\i_{sc} &= i_s \\v_s &= i_s R_s\end{aligned}$$

Thus,

$$R_s = \frac{v_{oc}}{i_{sc}}$$

$$(a) \quad v_s = v_{oc} = 10 \text{ V}$$

$$i_s = i_{sc} = 100 \text{ } \mu\text{A}$$

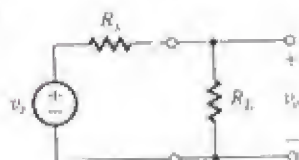
$$R_s = \frac{v_{oc}}{i_{sc}} = \frac{10 \text{ V}}{100 \text{ } \mu\text{A}} = 0.1 \text{ M}\Omega = 100 \text{ k}\Omega$$

$$(b) \quad v_s = v_{oc} = 0.1 \text{ V}$$

$$i_s = i_{sc} = 10 \text{ } \mu\text{A}$$

$$R_s = \frac{v_{oc}}{i_{sc}} = \frac{0.1 \text{ V}}{10 \text{ } \mu\text{A}} = 0.01 \text{ M}\Omega = 10 \text{ k}\Omega$$

1.23



$$\frac{v_o}{v_s} = \frac{R_L}{R_L + R_s}$$

$$v_o = v_s / \left(1 + \frac{R_s}{R_L}\right)$$

Thus,

$$\frac{v_o}{1 + \frac{R_s}{100}} = 30$$

and

$$\frac{v_o}{1 + \frac{R_s}{10}} = 10$$

Dividing (1) by (2) gives

$$\begin{aligned}\frac{1 + (R_s/10)}{1 + (R_s/100)} &= 3 \\ \Rightarrow R_s &= 28.6 \text{ k}\Omega\end{aligned}$$

Substituting in (2) gives

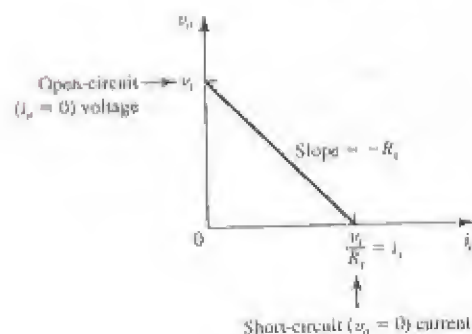
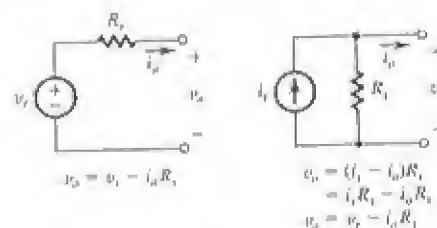
$$v_s = 38.6 \text{ mV}$$

The Norton current i_s can be found as

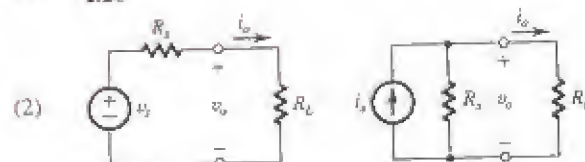
$$i_s = \frac{v_s}{R_s} = \frac{38.6 \text{ mV}}{28.6 \text{ k}\Omega} = 1.35 \text{ } \mu\text{A}$$

1.24 The observed output voltage is $1 \text{ mV}/^\circ\text{C}$ which is one half the voltage specified by the sensor, presumably under open-circuit conditions that is without a load connected. It follows that that sensor internal resistance must be equal to R_L , i.e., $10 \text{ k}\Omega$.

1.25



(1) 1.26



R_L represents the input resistance of the processor

For $v_o = 0.9 v_s$

$$0.9 = \frac{R_L}{R_L + R_s} \Rightarrow R_L = 9R_s$$

For $i_o = 0.9 i_s$

$$0.9 = \frac{R_s}{R_s + R_L} \Rightarrow R_L = R_s/9$$

1.27

Case	ω (rad/s)	f (Hz)	T (s)
a	6.28×10^0	1×10^0	1×10^{-9}
b	1×10^9	1.59×10^8	6.28×10^{-9}
c	6.28×10^{10}	1×10^{10}	1×10^{-10}
d	3.77×10^2	60	1.67×10^{-2}
e	6.28×10^3	1×10^3	1×10^{-3}
f	6.28×10^6	1×10^6	1×10^{-6}

1.28 (a) $V_{\text{peak}} = 117 \times \sqrt{2} = 165 \text{ V}$

(b) $V_{\text{rms}} = 33.9 / \sqrt{2} = 24 \text{ V}$

(c) $V_{\text{peak}} = 220 \times \sqrt{2} = 311 \text{ V}$

(d) $V_{\text{peak}} = 220 \times \sqrt{2} = 311 \text{ kV}$

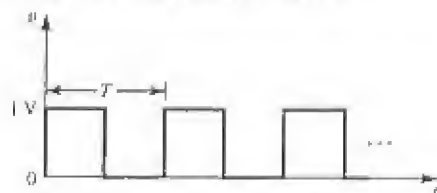
1.29 (a) $v = 10 \sin(2\pi \times 10^4 t), \text{ V}$

(b) $v = 120\sqrt{2} \sin(2\pi \times 60), \text{ V}$

(c) $v = 0.1 \sin(1000t), \text{ V}$

(d) $v = 0.1 \sin(2\pi \times 10^3 t), \text{ V}$

1.30 Comparing the given waveform to that described by Eq. 1.2 we observe that the given waveform has an amplitude of 0.5 V (1 V peak-to-peak) and its level is shifted up by 0.5 V (the first term in the equation). Thus the waveform look as follows



Average value = 0.5 V

Peak-to-peak value = 1 V

Lowest value = 0 V

Highest value = 1 V

Period $T = \frac{1}{f_0} = \frac{2\pi}{\omega_0} = 10^{-3} \text{ s}$

1.31 The two harmonics have the ratio $126/98 = 9/7$. Thus, these are the 7th and 9th harmonics. From Eq. 1.2 we note that the amplitudes of these two harmonics will have the ratio 7 to 9, which is confirmed by the measurement reported. Thus the fundamental will have a frequency of $98/7$ or 14 kHz and peak amplitude of $63 \times 7 = 441 \text{ mV}$. The rms value of the fundamental will be $441/\sqrt{2} = 312 \text{ mV}$. To find the peak-to-peak amplitude of the square wave we note

that $4V/\pi = 441 \text{ mV}$. Thus,

Peak-to-peak amplitude = $2V = 441 \times \frac{\pi}{2} = 693 \text{ mV}$

Period $T = \frac{1}{f} = \frac{1}{14 \times 10^3} = 71.4 \mu\text{s}$

1.32 To be barely audible by a relatively young listener, the 5th harmonic must be limited to 20 kHz; thus the fundamental will be 4 kHz. At the low end, hearing extends down to about 20 Hz. For the fifth and higher to be audible the fifth must be no lower than 20 Hz. Correspondingly, the fundamental will be at 4 Hz.

1.33 If the amplitude of the square wave is V_{sq} then the power delivered by the square wave to



a resistance R will be V_{sq}^2/R . If this power is to equal that delivered by a sine wave of peak amplitude \hat{V} then

$$\frac{V_{sq}^2}{R} = \frac{(\hat{V}/\sqrt{2})^2}{R}$$

Thus, $V_{sq} = \hat{V}/\sqrt{2}$. This result is independent of frequency.

1.34 Decimal Binary

0	0
5	101
8	1000
25	11001
57	111001

1.35 b_3, b_2, b_1, b_0 Value Represented

0	0	0	0	+0
0	0	0	1	+1
0	0	1	0	+2
0	0	1	1	+3
0	1	0	0	+4
0	1	0	1	+5
0	1	1	0	+6
0	1	1	1	+7
1	0	0	0	-0
1	0	0	1	-1
1	0	1	0	-2
1	0	1	1	-3
1	1	0	0	-4
1	1	0	1	-5
1	1	1	0	-6
1	1	1	1	-7

Note that there are two possible representation of zero: 0000 and 1000. For a 0.5-V step size, analog signals in the range ± 3.5 V can be represented

Input	Steps	Code
+2.5 V	+5	0101
-3.0 V	-6	1110
+2.7	+5	0101
-2.8	-6	1110

1.36 (a) For N bits there will be 2^N possible levels, from 0 to V_{FS} . Thus there will be $(2^N - 1)$ discrete steps from 0 to V_{FS} with the step size given by

$$\text{Step size} = \frac{V_{FS}}{2^N - 1}$$

This is the analog change corresponding to a change in the LSB. It is the value of the resolution of the ADC.

(b) The maximum error in conversion occurs when the analog signal value is at the middle of a step. Thus the maximum error is

$$\frac{1}{2} \times \text{step size} = \frac{1}{2} \frac{V_{FS}}{2^N - 1}$$

This is known as the quantization error.

$$\begin{aligned} \text{(c)} \quad \frac{10 \text{ V}}{2^N - 1} &\leq 5 \text{ mV} \\ 2^N - 1 &\geq 2000 \\ 2^N &\geq 2001 \Rightarrow N = 11 \end{aligned}$$

For $N = 11$,

$$\text{Resolution} = \frac{10}{2^{11} - 1} = 4.9 \text{ mV}$$

$$\text{Quantization error} = \frac{4.9}{2} = 2.4 \text{ mV}$$

1.37 When $b_i = 1$, the i th switch is in position 1 and a current $(V_{ref}/2^i R)$ flows to the output. Thus i_O will be the sum of all the currents corresponding to "1" bits, i.e.,

$$i_O = \frac{V_{ref}}{R} \left(\frac{b_1}{2^1} + \frac{b_2}{2^2} + \dots + \frac{b_N}{2^N} \right)$$

(b) b_N is the LSB
 b_1 is the MSB

$$\begin{aligned} \text{(c)} \quad i_{Omax} &= \frac{10 \text{ V}}{5 \text{ k}\Omega} \left(\frac{1}{2^1} + \frac{1}{2^2} + \frac{1}{2^3} + \frac{1}{2^4} + \frac{1}{2^5} + \frac{1}{2^6} \right) \\ &= 1.96875 \text{ mA} \end{aligned}$$

Corresponding to the LSB changing from 0 to 1 the output changes by $10/5 \times 1/2^6 = 0.03125$ mA.

1.38 There will be 44,100 samples per second with each sample represented by 16 bits. Thus the throughput or speed will be $44,100 \times 16 = 7.056 \times 10^5$ bits per second.

$$1.39 \text{ (a)} \quad A_v = \frac{v_o}{v_i} = \frac{10 \text{ V}}{100 \text{ mV}} = 100 \text{ V/V}$$

or, $20 \log 100 = 40 \text{ dB}$

$$\begin{aligned} A_i &= \frac{i_o}{i_i} = \frac{v_o/R_L}{i_i} = \frac{10 \text{ V}/100 \text{ }\Omega}{100 \text{ }\mu\text{A}} = \frac{0.1 \text{ A}}{100 \text{ }\mu\text{A}} \\ &= 1000 \text{ A/A} \end{aligned}$$

or, $20 \log 1000 = 60 \text{ dB}$

$$\begin{aligned} A_p &= \frac{v_o i_o}{v_i i_i} = \frac{v_o}{v_i} \times \frac{i_o}{i_i} = 100 \times 1000 \\ &= 10^5 \text{ W/W} \end{aligned}$$

or $10 \log 10^5 = 50 \text{ dB}$

$$\text{(b)} \quad A_v = \frac{v_o}{v_i} = \frac{2 \text{ V}}{10 \text{ }\mu\text{V}} = 2 \times 10^5 \text{ V/V}$$

or, $20 \log 2 \times 10^5 = 106 \text{ dB}$

$$\begin{aligned} A_i &= \frac{i_o}{i_i} = \frac{v_o/R_L}{i_i} = \frac{2 \text{ V}/10 \text{ k}\Omega}{100 \text{ nA}} \\ &= \frac{0.2 \text{ mA}}{100 \text{ nA}} = \frac{0.2 \times 10^{-3}}{100 \times 10^{-9}} = 2000 \text{ A/A} \end{aligned}$$

or $20 \log A_i = 66 \text{ dB}$

$$\begin{aligned} A_p &= \frac{v_o i_o}{v_i i_i} = \frac{v_o}{v_i} \times \frac{i_o}{i_i} \\ &= 2 \times 10^5 \times 2000 \\ &= 4 \times 10^8 \text{ W/W} \end{aligned}$$

or $10 \log A_p = 86 \text{ dB}$

$$\text{(c)} \quad A_v = \frac{v_o}{v_i} = \frac{10 \text{ V}}{1 \text{ V}} = 10 \text{ V/V}$$

or, $20 \log 10 = 20 \text{ dB}$

$$\begin{aligned} A_i &= \frac{i_o}{i_i} = \frac{v_o/R_L}{i_i} = \frac{10 \text{ V}/10 \text{ }\Omega}{1 \text{ mA}} \\ &= \frac{1 \text{ A}}{1 \text{ mA}} = 1000 \text{ A/A} \end{aligned}$$

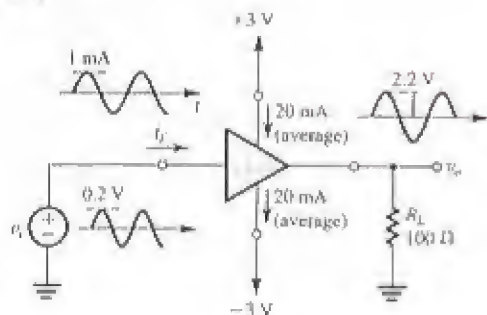
or, $20 \log 1000 = 60 \text{ dB}$

$$A_p = \frac{v_o i_o}{v_i i_i} = \frac{v_o}{v_i} \times \frac{i_o}{i_i}$$

$$= 10 \times 1000 = 10^4 \text{ W/W}$$

or $10 \log_{10} A_p = 40 \text{ dB}$

1.40



$$A_v = \frac{v_o}{v_i} = \frac{2.2}{0.2}$$

$$= 11 \text{ V/V}$$

or $20 \log 11 = 20.8 \text{ dB}$

$$A_i = \frac{i_o}{i_i} = \frac{2.2 \text{ V} / 100 \Omega}{1 \text{ mA}}$$

$$= \frac{22 \text{ mA}}{1 \text{ mA}} = 22 \text{ A/A}$$

or, $20 \log A_i = 26.8 \text{ dB}$

$$A_p = \frac{p_o}{p_i} = \frac{(2.2/\sqrt{2})^2 / 100}{\frac{0.2}{\sqrt{2}} \times \frac{10^{-3}}{\sqrt{2}}}$$

$$= 242 \text{ W/W}$$

or, $10 \log A_p = 23.8 \text{ dB}$

Supply power = $2 \times 3 \text{ V} \times 20 \text{ mA} = 120 \text{ mW}$

$$\text{Output power} = \frac{v_{rms}^2}{R_L} = \frac{(2.2/\sqrt{2})^2}{100 \Omega} = 24.2 \text{ mW}$$

$$\text{Input power} = \frac{24.2}{242} = 0.1 \text{ mW (negligible)}$$

Amplifier dissipation \approx Supply power - Output power
 $= 120 - 24.2 = 95.8 \text{ mW}$

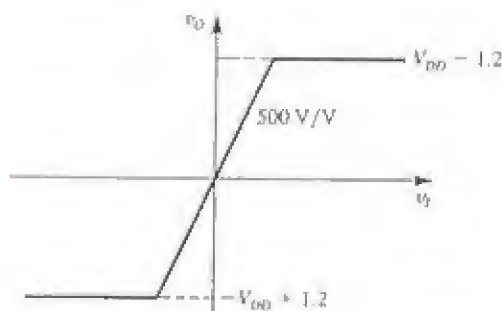
$$\text{Amplifier efficiency} = \frac{\text{Output power}}{\text{Supply power}} \times 100$$

$$= \frac{24.2}{120} \times 100 = 20.2\%$$

1.41 For $V_{DD} = 5 \text{ V}$:

The largest undistorted sine-wave output is of 3.8-V peak amplitude or $3.8/\sqrt{2} = 2.7 \text{ V}_{rms}$. Input needed is 5.4 mV_{rms} .

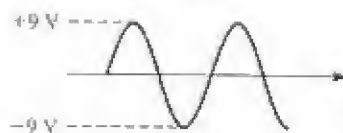
Supplies are V_{DD} and $-V_{DD}$



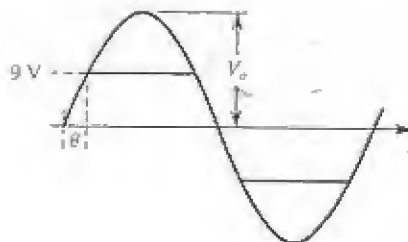
For $V_{DD} = 10 \text{ V}$, the largest undistorted sine-wave output is of 8.8-V peak amplitude or 6.2 V_{rms} . Input needed is 12.4 mV_{rms} .

For $V_{DD} = 15 \text{ V}$, the largest undistorted sine-wave output is of 13.8-V peak amplitude or 9.8 V_{rms} . The input needed is $9.8 \text{ V} / 500 = 19.6 \text{ mV}_{rms}$.

1.42 (a) For an output whose extremes are just at the edge of clipping, i.e., an output of 9-V_{peak} , the input must have $9 \text{ V} / 1000 = 9 \text{ mV}_{peak}$.



(b) For an output that is clipping 90% of the time, $\theta = 0.1 \times 90^\circ = 9^\circ$ and $V_p \sin 9^\circ = 9 \text{ V} \Rightarrow V_p = 57.5 \text{ V}$ which of course does not occur as the output saturates at $\pm 9 \text{ V}$. To produce this result, the input peak must be $57.5 / 1000 = 57.5 \text{ mV}$.

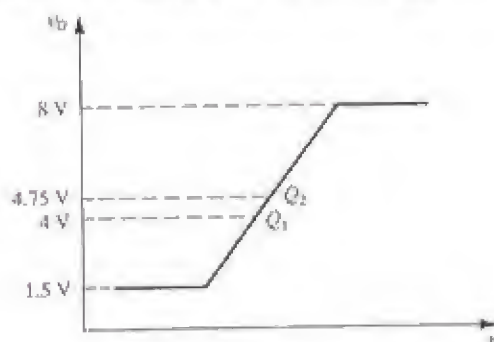


- (c) For an output that is clipping 99% of the time,
 $\theta = 0.01 \times 90^\circ = 0.9^\circ$

$$V_p \sin 0.9^\circ = 9 \text{ V} \\ \Rightarrow V_p = 573 \text{ V}$$

and the input must be $573 \text{ V}/1000$ or $0.573 \text{ V}_{\text{peak}}$.

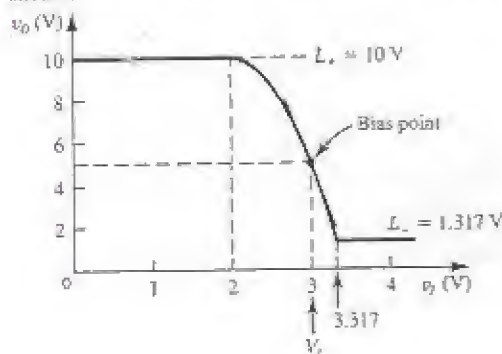
1.43 When the amplifier is biased at 4 V (i.e., at point Q_1), the maximum possible amplitude of a sine-wave output without clipping is $(4 - 1.5) = 2.5 \text{ V}_{\text{peak}}$.



To obtain the largest undistorted sine wave output possible with this amplifier, it must be biased halfway between the saturation levels, i.e., at $V_O = (8 + 1.5)/2 = 4.75 \text{ V}$ (point Q_2) and the resulting output will have a peak value of $8 - 4.75 = 4.75 - 1.50 = 3.25 \text{ V}$.

- 1.44** $v_O = 10 - 5(v_I - 2)^2$, $2 \leq v_I \leq v_O + 2$, $v_O \geq 0$
 (b) For $v_I \leq 2 \text{ V}$, $v_O = 10 \text{ V}$.

The upper limit on v_I is found by substituting $v_I = v_O + 2$, that is, $v_O = v_I - 2$ in the transfer characteristic. The result is $v_O = 10 - 5v_O^2$ whose solution is $v_O = 1.317 \text{ V}$ and the corresponding $v_I = 3.317 \text{ V}$. To obtain a sketch of v_O versus v_I , we evaluate v_O for values of v_I in the range 2 V to 3.317 V . The result is the following sketch:



- (b) To obtain $V_O = 5 \text{ V}$ we bias at $V_I = 3 \text{ V}$.

(c) Small-signal gain at bias point $= \left. \frac{\partial v_O}{\partial v_I} \right|_{V_I=3\text{V}}$
 $= -5 \times 2(V_I - 2) = -10 \text{ V/V}$

- (d) $v_i = 3 + V_1 \cos \omega t$

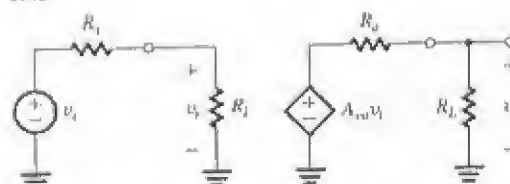
$$\begin{aligned} v_O &= 10 - 5(3 + V_1 \cos \omega t - 2)^2 \\ &= 10 - 5(1 + 2V_1 \cos \omega t + V_1^2 \cos^2 \omega t) \\ &= 5 - 10V_1 \cos \omega t - 5V_1^2 \left(\frac{1}{2} + \frac{1}{2} \cos 2\omega t \right) \\ &= \underbrace{(5 - 2.5V_1^2)}_{\text{dc}} - \underbrace{10V_1 \cos \omega t}_{\text{Fundamental}} - \underbrace{2.5V_1^2 \cos 2\omega t}_{\text{2nd harmonic}} \end{aligned}$$

For 1% second-harmonic distortion: $2.5V_1^2/10V_1 = 0.01$

Thus,

$$V_1 = \frac{10 \times 0.01}{2.5} \text{ V} = 40 \text{ mV}$$

1.45



$$\frac{v_o}{v_i} = \frac{R_L}{R_i + R_i} \times A_v \times \frac{R_L}{R_L + R_o}$$

(a) $\frac{v_o}{v_i} = \frac{10R_i}{10R_i + R_i} \times A_v \times \frac{10R_o}{10R_o + R_o}$
 $= \frac{10}{11} \times 10 \times \frac{10}{11} = 8.26 \text{ V/V}$

or, $20 \log 8.26 = 18.3 \text{ dB}$

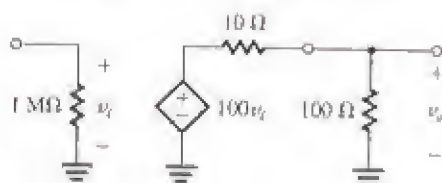
(b) $\frac{v_o}{v_i} = \frac{R_i}{R_i + R_i} \times A_v \times \frac{R_o}{R_o + R_o}$
 $= 0.5 \times 10 \times 0.5 = 2.5 \text{ V/V}$

or, $20 \log 2.5 = 8 \text{ dB}$

(c) $\frac{v_o}{v_i} = \frac{R_i/10}{(R_i/10) + R_i} \times A_v \times \frac{R_o/10}{(R_o/10) + R_o}$
 $= \frac{1}{11} \times 10 \times \frac{1}{11} = 0.083 \text{ V/V}$

or $20 \log 0.083 = -21.6 \text{ dB}$

1.46 $20 \log A_{v_o} = 40 \text{ dB} \Rightarrow A_{v_o} = 100 \text{ V/V}$



$$A_v = \frac{v_o}{v_i} = 100 \times \frac{100}{100 + 10} = 90.9 \text{ V/V}$$

or, $20 \log 90.9 = 39.1 \text{ dB}$

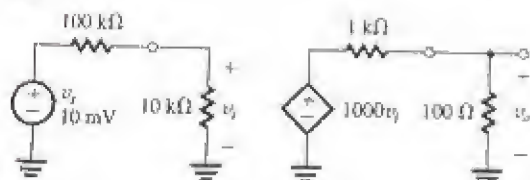
$$A_p = \frac{v_o^2 / 100 \Omega}{v_i^2 / 1 \text{ M}\Omega} = A_v^2 \times 10^4 = 8.3 \times 10^7 \text{ W/W}$$

or $10 \log (8.3 \times 10^7) = 79.1 \text{ dB}$

For a peak output sine-wave current of 100 mA , the peak output voltage will be $100 \text{ mA} \times 100 \Omega = 10 \text{ V}$. Correspondingly v_i will be a sine wave with a peak value of $10 \text{ V}/A_v = 10/90.9$ or an rms value of $10/(90.9 \times \sqrt{2}) = 0.08 \text{ V}$.

$$\text{Corresponding output power} = (10/\sqrt{2})^2 / 100 \Omega = 0.5 \text{ W}$$

1.47

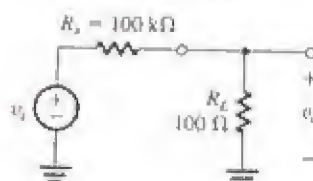


$$\frac{v_o}{v_i} = \frac{10 \text{ k}\Omega}{10 \text{ k}\Omega + 100 \text{ k}\Omega} \times 1000 \times \frac{100 \Omega}{100 \Omega + 1 \text{ k}\Omega} = \frac{10}{110} \times 1000 \times \frac{100}{1100} = 8.26 \text{ V/V}$$

The signal loses about 90% of its strength when connected to the amplifier input (because $R_i = R_s/10$). Also, the output signal of the amplifier loses approximately 90% of its strength when the load is connected

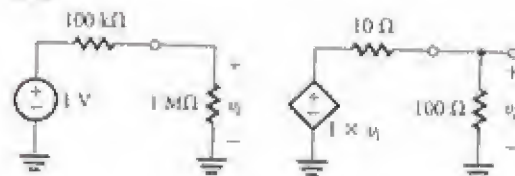
(because $R_L = R_o/10$). Not a good design! Nevertheless, if the source were connected directly to the load,

$$\frac{v_o}{v_i} = \frac{R_L}{R_L + R_s} = \frac{100 \Omega}{100 \Omega + 100 \text{ k}\Omega} = 0.001 \text{ V/V}$$



which is clearly a much worse situation. Indeed inserting the amplifier increases the gain by a factor $8.3/0.001 = 8300$.

1.48



$$v_o = 1 \text{ V} \times \frac{1 \text{ M}\Omega}{1 \text{ M}\Omega + 100 \text{ k}\Omega} \times 1 \times \frac{100 \Omega}{100 \Omega + 10 \Omega} = \frac{1}{1.1} \times \frac{100}{110} = 0.83 \text{ V}$$

$$\text{Voltage gain} = \frac{v_o}{v_i} = 0.83 \text{ V/V} \quad \text{or} \quad -1.6 \text{ dB}$$

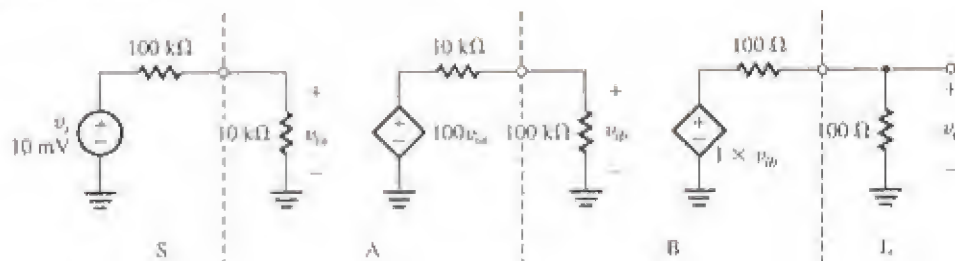
$$\text{Current gain} = \frac{v_o / 100 \Omega}{v_i / 1.1 \text{ M}\Omega} = 0.83 \times 1.1 \times 10^4 = 9091 \text{ A/A} \quad \text{or} \quad 79.2 \text{ dB}$$

$$\text{Power gain} = \frac{v_o^2 / 100 \Omega}{v_i^2 / 1.1 \text{ M}\Omega} = 7578 \text{ W/W}$$

or $10 \log 7578 = 38.8 \text{ dB}$

(This takes into acct. the power dissipated in the internal resistance of the source.)

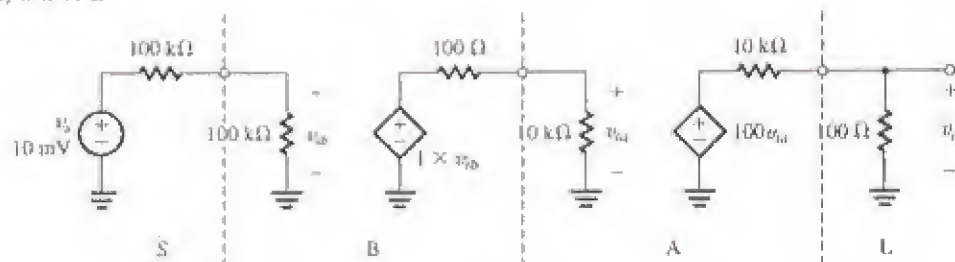
1.50 Case (a) S-A-B-L.



$$\frac{v_o}{v_s} = \frac{10}{10 + 100} \times 100 \times \frac{100}{100 + 10} \times 1 \times \frac{100}{100 + 100} = 4.1 \text{ V/V}$$

$$\text{or } 20 \log 4.1 = 12.3 \text{ dB}$$

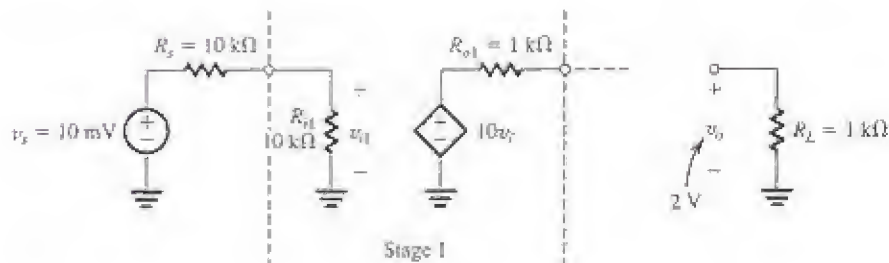
Case (b) S-B-A-L.



$$\begin{aligned} \frac{v_o}{v_s} &= \frac{100}{100 + 100} \times 1 \times \frac{10 \text{ k}\Omega}{10 \text{ k}\Omega + 100 \text{ }\Omega} \times 100 \times \frac{100 \text{ }\Omega}{100 \text{ }\Omega + 10 \text{ k}\Omega} \\ &= 0.5 \times \frac{10}{10.1} \times 100 \times \frac{0.1}{10.1} \\ &= 0.5 \text{ V/V or } -6 \text{ dB} \end{aligned}$$

Thus, obviously case (a) i.e., SABL is preferred.

1.51

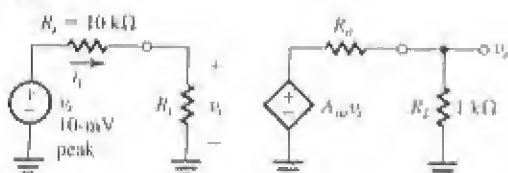


Required overall voltage gain $= 2 \text{ V} / 10 \text{ mV} = 200 \text{ V/V}$. Each stage is capable of providing a *maximum* voltage gain of 10 (the open-circuit gain value). For n stages in cascade the maximum (unattainable) voltage gain is 10^n . We thus see that we need at least 3 stages. For 3 stages, the overall voltage gain obtained is

$$\frac{v_o}{v_i} = \frac{10}{10+10} \times 10 \times \frac{10}{1+10} \times 10 \times \frac{10}{1+10} \times 10 \times \frac{1}{1+1} = 206.6 \text{ V/V}$$

Thus, three stages suffice and provide a gain slightly larger than required. The output voltage actually obtained is $10 \text{ mV} \times 206.6 = 2.07 \text{ V}$.

1.53



(a) Required voltage gain $= \frac{v_o}{v_i} = \frac{3 \text{ V}}{0.01 \text{ V}} = 300 \text{ V/V}$

(b) The smallest R_L allowed is obtained from

$$0.1 \mu\text{A} = \frac{10 \text{ mV}}{R_s + R_L} \Rightarrow R_s + R_L = 100 \text{ k}\Omega$$

Thus $R_L = 90 \text{ k}\Omega$.

For $R_L = 90 \text{ k}\Omega$, $i_i = 0.1 \mu\text{A}$ peak, and

$$\text{Overall current gain} = \frac{v_o / R_L}{i_i} = \frac{3 \text{ mA}}{0.1 \mu\text{A}} = 3 \times 10^4 \text{ A/A}$$

$$\begin{aligned} \text{Overall power gain} &= \frac{v_{o(\text{rms})}^2 / R_L}{v_{i(\text{rms})} \times i_{i(\text{rms})}} \\ &= \frac{\left(\frac{3}{\sqrt{2}}\right)^2 / 1000}{\left(\frac{10 \times 10^{-3}}{\sqrt{2}}\right) \times \left(\frac{0.1 \times 10^{-6}}{\sqrt{2}}\right)} \\ &= 9 \times 10^6 \text{ W/W} \end{aligned}$$

(This takes into acct. the power dissipated in the internal resistance of the source.)

(c) If $(A_v v_i)$ has its peak value limited to 5 V, the largest value of R_o is found from

$$5 \times \frac{R_L}{R_L + R_o} = 3 \Rightarrow R_o = \frac{2}{3} R_L = 667 \Omega$$

(If R_o were greater than this value, the output voltage across R_L would be less than 3 V.)

(d) For $R_L = 90 \text{ k}\Omega$ and $R_o = 667 \Omega$, the required value of A_v can be found from

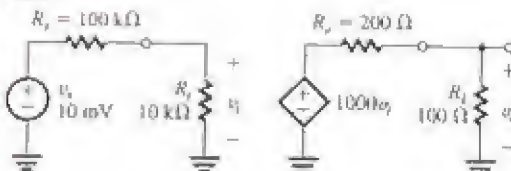
$$300 \text{ V/V} = \frac{90}{90+10} \times A_v \times \frac{1}{1+0.667} \Rightarrow A_v = 555.7 \text{ V/V}$$

(e) $R_L = 100 \text{ k}\Omega$ ($1 \times 10^5 \Omega$)

$R_o = 100 \Omega$ ($1 \times 10^2 \Omega$)

$$300 = \frac{100}{100+10} \times A_v \times \frac{1000}{1000+100} \Rightarrow A_v = 363 \text{ V/V}$$

1.54



(a) $v_o = 10 \text{ mV} \times \frac{10}{10+100} \times 1000 \times \frac{100}{100+200} = 303 \text{ mV}$

(b) $\frac{v_o}{v_i} = \frac{303 \text{ mV}}{10 \text{ mV}} = 30.3 \text{ V/V}$

(c) $\frac{v_o}{v_i} = 1000 \times \frac{100}{100+200} = 333.3 \text{ V/V}$

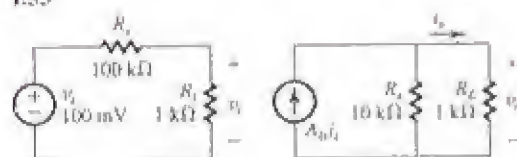
(d)



Connect a resistance R_p in parallel with the input and select its value from

$$\begin{aligned}\frac{(R_p \parallel R_i)}{(R_p \parallel R_i) + R_i} &= \frac{1}{2} \frac{R_i}{R_i + R_i} \\ \Rightarrow 1 + \frac{R_i}{R_p \parallel R_i} &= 22 \Rightarrow R_p \parallel R_i = \frac{R_i}{21} = \frac{100}{21} \\ \Rightarrow \frac{1}{R_p} + \frac{1}{R_i} &= \frac{21}{100} \\ R_p &= \frac{1}{0.21 - 0.1} = 9.1 \text{ k}\Omega\end{aligned}$$

1.55



(a) Current gain $= \frac{i_o}{i_i}$

$$\begin{aligned}&= A_v \frac{R_o}{R_o + R_L} \\ &= 100 \frac{10}{11} \\ &= 90.9 \frac{\text{A}}{\text{A}} = 39.2 \text{ dB}\end{aligned}$$

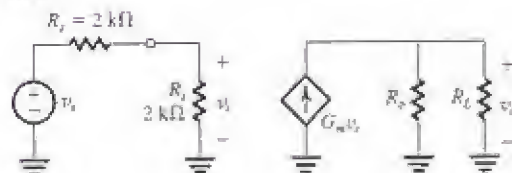
(b) Voltage gain $= \frac{v_o}{v_i}$

$$\begin{aligned}&= \frac{i_o}{i_i} \frac{R_i}{R_i + R_i} \\ &= 90.9 \times \frac{1}{101} \\ &= 0.9 \text{ V/V} = -0.9 \text{ dB}\end{aligned}$$

(c) Power gain $= A_p = \frac{v_o i_o}{v_i i_i}$

$$\begin{aligned}&= 0.9 \times 90.9 \\ &= 81.8 \text{ W/W} = 19.1 \text{ dB}\end{aligned}$$

1.56



$$G_m = 40 \text{ mA/V}$$

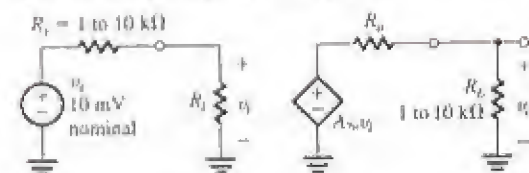
$$R_o = 20 \text{ k}\Omega$$

$$R_L = 1 \text{ k}\Omega$$

$$\begin{aligned}v_i &= v_i \frac{R_i}{R_i + R_i} \\ &= v_i \frac{2}{2+2} = \frac{v_i}{2} \\ v_o &= G_m v_i (R_L \parallel R_o) \\ &= 40 \frac{20 \times 1}{20+1} v_i \\ &= 40 \frac{20}{21} \frac{v_i}{2}\end{aligned}$$

$$\text{Overall voltage gain} = \frac{v_o}{v_i} = 19.05 \text{ V/V}$$

1.57 A voltage amplifier is required,



To limit the change in v_o to 10% as R_i varies from 1 to 10 kΩ we select R_i sufficiently large;

$$R_i \geq 10 R_{i \max}$$

Thus $R_i = 100 \text{ k}\Omega$.

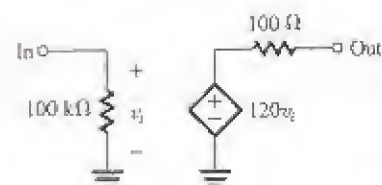
To limit the change in v_o corresponding to R_L varying in the range 1 to 10 kΩ, to 10%, we select R_o sufficiently small;

$$R_o \leq R_{L \min} / 10$$

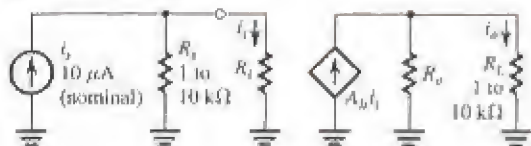
Thus,

$$R_o = 100 \Omega$$

$$\begin{aligned}v_{o \min} &= v_i \frac{R_i}{R_i + R_{i \max}} A_v \frac{R_{L \min}}{R_{L \min} + R_o} \\ 1 &= 0.01 \frac{100}{100+10} A_v \frac{1000}{1000+100} \\ \Rightarrow A_v &= 121 \text{ V/V}\end{aligned}$$



1.58 Current amplifier.



To limit the change in i_o resulting from R_L varying over the range 1 to 10 k Ω , to 10% we select R_o sufficiently low so that,

$$R_o \leq R_{Lmin} / 10$$

Thus, $R_o = 100 \Omega$

To limit the change in i_o as R_s changes from 1 to 10 k Ω , to 10% we select R_o sufficiently large;

$$R_o \geq 10 R_{Lmax}$$

Thus, $R_o = 100 \text{ k}\Omega$

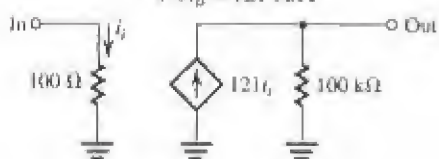
Now for $i_s = 10 \mu A$,

$$i_{o,min} = 10^{-5} \frac{R_{s,min}}{R_{s,min} + R_s} A_{ib} \frac{R_o}{R_o + R_{L,max}}$$

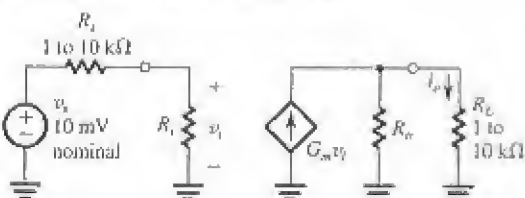
Thus,

$$10^{-3} = 10^{-5} \frac{1000}{1000 + 100} A_{ib} \frac{100}{100 + 10}$$

$$\Rightarrow A_{ib} = 121 \text{ A/A}$$



1.59 Transconductance amplifier.



For R_L varying in the range 1 to 10 k Ω , and Δi_o limited to 10% we have to select R_o sufficiently large;

$$R_o \geq 10 R_{Lmax}$$

$$R_o = 100 \text{ k}\Omega$$

For R_s varying in the range 1 to 10 k Ω , the change in i_o can be kept to 10% if R_o is selected sufficiently large;

$$R_o \geq R_{Lmax}$$

Thus $R_o = 100 \text{ k}\Omega$

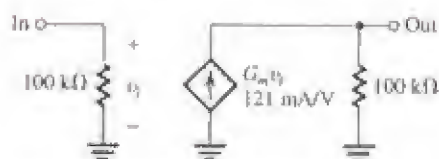
For $v_s = 10 \text{ mV}$,

$$i_{o,min} = 10^{-2} \frac{R_s}{R_s + R_{s,max}} G_m \frac{R_o}{R_o + R_{L,max}}$$

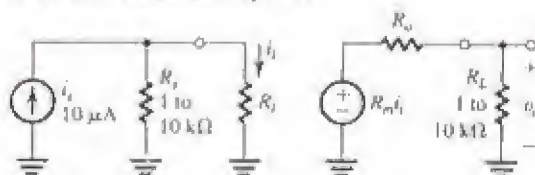
$$10^{-3} = 10^{-2} \frac{100}{100 + 10} G_m \frac{100}{100 + 10}$$

$$G_m = 1.21 \times 10^{-3} \text{ A/V}$$

$$= 121 \text{ mA/V}$$



1.60 Transresistance amplifier



To limit Δv_o to 10% corresponding to R_s varying in the range 1 to 10 k Ω , we select R_o sufficiently low;

$$R_o \leq \frac{R_{s,min}}{10}$$

Thus, $R_o = 100 \Omega$

To limit Δv_o to 10% while R_L varies over the range 1 to 10 k Ω , we select R_o sufficiently low;

$$R_o \leq R_{Lmin} / 10$$

Thus, $R_o = 100 \Omega$

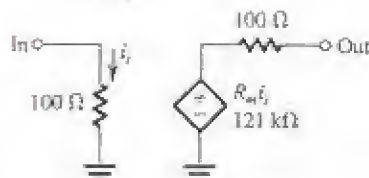
Now, for $i_s = 10 \mu A$,

$$v_{o,min} = 10^{-5} \frac{R_{s,min}}{R_{s,min} + R_s} R_m \frac{R_{L,min}}{R_{L,min} + R_o}$$

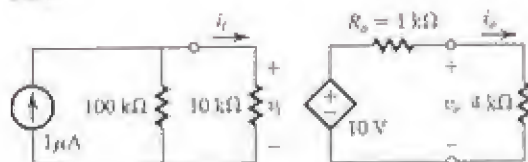
$$1 = 10^{-5} \frac{1000}{1000 + 100} R_m \frac{1000}{1000 + 100}$$

$$\Rightarrow R_m = 1.21 \times 10^5$$

$$= 121 \text{ k}\Omega$$



1.64



$$R_o = \frac{\text{Open-circuit output voltage}}{\text{Short-circuit output current}} = \frac{10 \text{ V}}{10 \text{ mA}} = 1 \text{ k}\Omega$$

$$v_o = 10 \times \frac{4}{1+4} = 8 \text{ V}$$

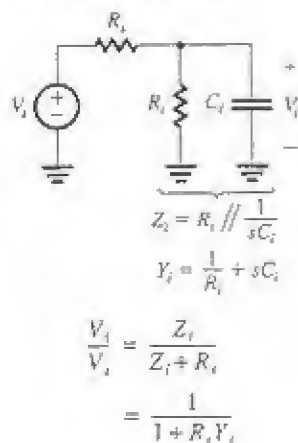
$$A_v = \frac{v_o}{v_i} = \frac{8}{1 \times 10^{-5} \times (100 \parallel 10) \times 10^3} = 888 \text{ V/V or } 58.9 \text{ dB}$$

$$A_i = \frac{i_o}{i_i} = \frac{v_o/R_L}{10^{-5} \times \frac{100}{100+10}} = \frac{8/(4 \times 10^3)}{10^{-5} \times \frac{100}{110}} = 2200 \text{ A/A or } 66.8 \text{ dB}$$

$$A_p = \frac{v_o^2/R_L}{i_i^2 R_i} = \frac{8^2/(4 \times 10^3)}{\left(10^{-5} \times \frac{100}{100+10}\right)^2 10 \times 10^3} = 19.36 \times 10^3 \text{ W/W or } 62.9 \text{ dB}$$

$$\begin{aligned} \text{Overall current gain} &= \frac{i_o}{1 \mu\text{A}} \\ &= \frac{v_o/R_L}{1 \mu\text{A}} = \frac{8/(4 \times 10^3)}{10^{-6}} = 2000 \text{ A/A or } 66 \text{ dB} \end{aligned}$$

1.65 Using the voltage divider rule



$$\begin{aligned} &= \frac{1}{1 + R_i \left(\frac{1}{R_i} + sC_i \right)} \\ &= \frac{1}{1 + \frac{R_i}{R_i} + sC_i R_i} = \frac{1/\left(1 + \frac{R_i}{R_i}\right)}{1 + sC_i \frac{R_i}{1 + \frac{R_i}{R_i}}} \\ &= \frac{1}{1 + \frac{R_i}{R_i}} \frac{1}{1 + sC_i \left(\frac{R_i R_i}{R_i + R_i} \right)} \\ &= \frac{R_i}{R_i + R_i} \frac{1}{1 + sC_i (R_i \parallel R_i)} \end{aligned}$$

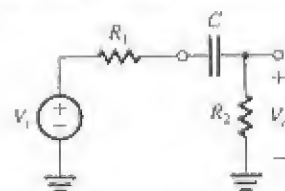
This transfer function is of the STC low-pass type with a dc gain $K = R_i/(R_i + R_i)$ and a 3-dB frequency $\omega_b = 1/C_i(R_i \parallel R_i)$.

For $R_i = 20 \text{ k}\Omega$, $R_i = 80 \text{ k}\Omega$, and $C_i = 5 \text{ pF}$,

$$\omega_b = \frac{1}{5 \times 10^{-12} \times \frac{20 \times 80}{20 + 80} \times 10^3} = 1.25 \times 10^7 \text{ rad/s}$$

$$f_b = \frac{\omega_b}{2\pi} = \frac{1.25 \times 10^7}{2\pi} \approx 2 \text{ MHz}$$

1.66 Using the voltage-divider rule,



$$\begin{aligned} T(s) = \frac{V_o}{V_i} &= \frac{R_2}{R_2 + R_i + \frac{1}{sC}} \\ &= \frac{R_2}{R_i + R_2} \frac{s}{s + \frac{1}{C(R_i + R_2)}} \end{aligned}$$

which from Table 1.2 is of the high-pass type with

$$K = \frac{R_2}{R_i + R_2}$$

and

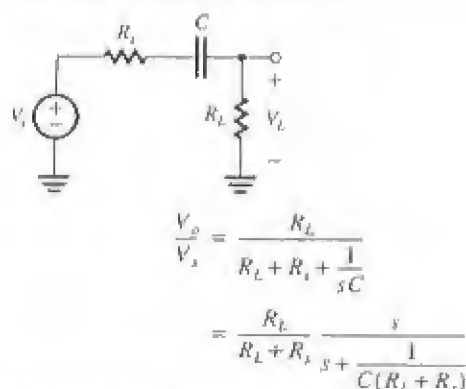
$$\omega_b = \frac{1}{C(R_i + R_2)}$$

As a further verification that this is a high-pass network and $T(s)$ is a high-pass transfer function we observe as at $s = 0$, $T(s) = 0$; and that as $s \rightarrow \infty$, $T(s) = R_2/(R_1 + R_2)$. Also, from the circuit observe as at $s \rightarrow \infty$, $(1/sC) \rightarrow 0$ and $V_o/V_i = R_2/(R_1 + R_2)$. Now, for $R_1 = 10 \text{ k}\Omega$, $R_2 = 40 \text{ k}\Omega$, and $C = 0.1 \text{ }\mu\text{F}$,

$$f_0 = \frac{\omega_0}{2\pi} = \frac{1}{2\pi \times 0.1 \times 10^{-6} (10 + 40) \times 10^3} = 31.8 \text{ Hz}$$

$$|T(j\omega_0)| = \frac{K}{\sqrt{2}} = \frac{40}{10 + 40} \frac{1}{\sqrt{2}} = 0.57 \text{ V/V}$$

1.67 Using the voltage divider rule,



which is of the high-pass STC type (see Table 1.2) with

$$K = \frac{R_L}{R_L + R_i} \quad \omega_0 = \frac{1}{C(R_L + R_i)}$$

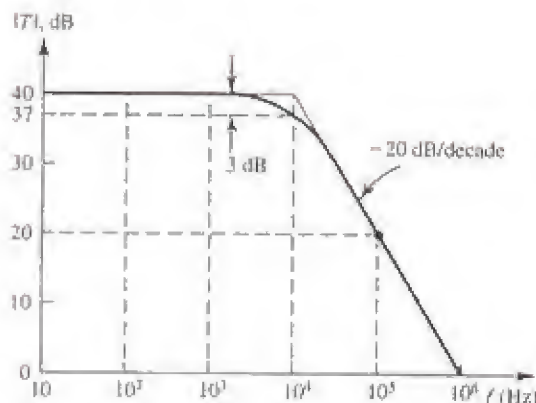
For $f_0 \leq 10 \text{ Hz}$

$$\frac{1}{2\pi C(R_L + R_i)} \leq 10$$

$$\Rightarrow C \geq \frac{1}{2\pi \times 10(20 + 5) \times 10^3}$$

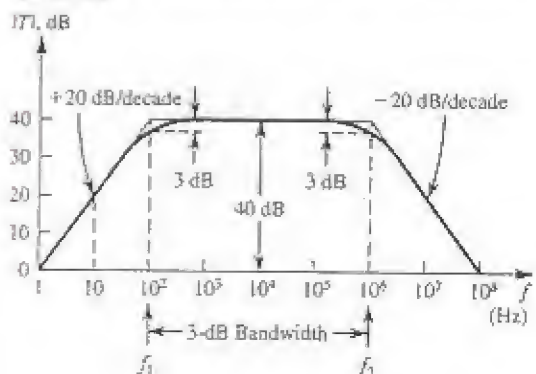
Thus, the smallest value of C that will do the job is $C = 0.64 \text{ }\mu\text{F}$.

1.68 The given measured data indicate that this amplifier has a low-pass STC frequency response with a low-frequency gain of 40 dB, and a 3-dB frequency of 10^4 Hz . From our knowledge of the Bode plots for low-pass STC networks (Figure . . .) we can complete the Table entries and sketch the amplifier frequency response.



$f \text{ (Hz)}$	$ T \text{ (dB)}$	$\angle T \text{ (degrees)}$
1000	40	-5.7°
10^4	37	-45°
10^5	20	-84.3°
10^6	0	-90°

1.69 From our knowledge of the Bode plots of STC low-pass and high-pass networks we see that this amplifier has a mid-band gain of 40 dB, a low-frequency response of the high-pass STC type with $f_{\text{sub}} = 10^2 \text{ Hz}$, and a high-frequency response of the low-pass STC type with $f_{\text{sub}} = 10^6 \text{ Hz}$. We thus can sketch the amplifier frequency response and complete the table entries as follows



$f \text{ (Hz)}$	1	10	10^2	10^3	10^4	10^5	10^6	10^7	10^8
$ T \text{ (dB)}$	0	20	37	40	40	40	37	20	0

1.72 Since the overall transfer function is that of three identical STC LP circuits in cascade (but with no loading effects since the buffer amplifiers have input and zero output resistances) the overall gain will drop by 3 dB below the value at dc at the frequency for which the gain of each STC circuit is 1 dB down. This frequency is found as follows: The transfer function of each STC circuit is

$$T(s) = \frac{1}{1 + \frac{s}{\omega_0}}$$

where

$$\omega_0 = 1/CR$$

Thus,

$$|T(j\omega)| = \frac{1}{\sqrt{1 + \left(\frac{\omega}{\omega_0}\right)^2}}$$

$$20 \log \frac{1}{\sqrt{1 + \left(\frac{\omega_{1dB}}{\omega_0}\right)^2}} = -1$$

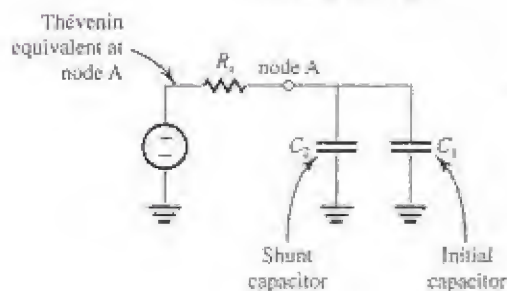
$$\Rightarrow 1 + \left(\frac{\omega_{1dB}}{\omega_0}\right)^2 = 10^{0.1}$$

$$\omega_{1dB} = 0.51 \omega_0$$

$$\omega_{1dB} = 0.51 / CR$$

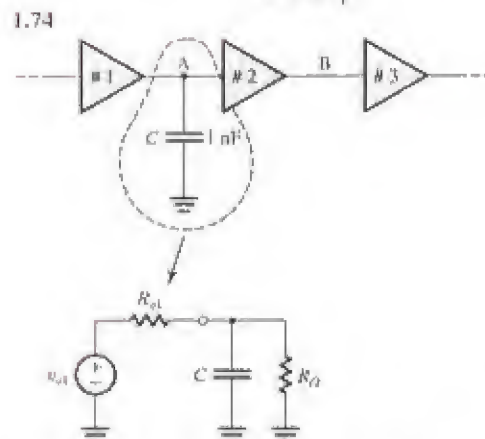
1.73 $R_1 = 100 \text{ k}\Omega$, since the 3-dB frequency is reduced by a very high factor (from 6 MHz to 120 kHz) C_2 must be much larger than C_1 . Thus, neglecting C_1 we find C_2 from

$$\begin{aligned} 120 \text{ kHz} &= \frac{1}{2\pi C_2 R_1} \\ &= \frac{1}{2\pi C_2 \times 10^5} \\ \Rightarrow C_2 &= 13.3 \text{ pF} \end{aligned}$$



If the original 3-dB frequency (6 MHz) is attributable to C_1 then

$$\begin{aligned} 6 \text{ MHz} &= \frac{1}{2\pi C_1 R_1} \\ \Rightarrow C_1 &= \frac{1}{2\pi \times 6 \times 10^6 \times 10^5} \\ &= 0.26 \text{ pF} \end{aligned}$$



Since when C is connected the 3-dB frequency is reduced by a large factor, the value of C must be much larger than whatever parasitic capacitance originally existed at node A (i.e., between A and ground). Furthermore, it must be that C is now the dominant determinant of the amplifier 3-dB frequency (i.e., it is dominating over whatever may be happening at node B or anywhere else in the amplifier). Thus, we can write

$$\begin{aligned} 150 \text{ kHz} &= \frac{1}{2\pi C(R_{o1} \parallel R_{i2})} \\ \Rightarrow (R_{o1} \parallel R_{i2}) &= \frac{1}{2\pi \times 150 \times 10^3 \times 1 \times 10^{-9}} \\ &= 1.06 \text{ k}\Omega \end{aligned}$$

Now $R_{i2} = 100 \text{ k}\Omega$,

Thus $R_{o1} = 1.07 \text{ k}\Omega$

Similarly, for node B,

$$\begin{aligned} 15 \text{ kHz} &= \frac{1}{2\pi C(R_{o2} \parallel R_{i3})} \\ \Rightarrow R_{o2} \parallel R_{i3} &= \frac{1}{2\pi \times 15 \times 10^3 \times 1 \times 10^{-9}} \\ &= 10.6 \text{ k}\Omega \end{aligned}$$

$$R_{o2} = 11.9 \text{ k}\Omega$$

She should connect a capacitor of value C_p to node B where C_p can be found from,

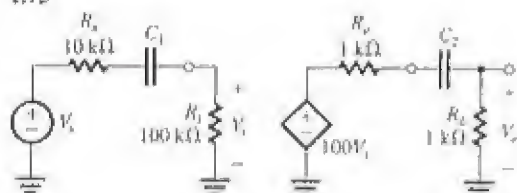
$$10 \text{ kHz} = \frac{1}{2\pi C_p (R_{o2} \parallel R_{i3})}$$

$$\Rightarrow C_p = \frac{1}{2\pi \times 10 \times 10^3 \times 10.6 \times 10^3}$$

$$\approx 1.5 \text{ nF}$$

Note that if she chooses to use node A she would need to connect a capacitor 10 times larger!

1.75



For the input circuit, the corner frequency f_{01} is found from

$$f_{01} = \frac{1}{2\pi C_1 (R_s + R_L)}$$

For $f_{01} \leq 100 \text{ Hz}$,

$$\frac{1}{2\pi C_1 (10 + 100) \times 10^3} \leq 100$$

$$\Rightarrow C_1 \geq \frac{1}{2\pi \times 110 \times 10^3 \times 10^3} = 4.4 \times 10^{-9}$$

Thus we select $C_1 = 1 \times 10^{-7} \text{ F} = 0.1 \mu\text{F}$. The actual corner frequency resulting from C_1 will be

$$f_{01} = \frac{1}{2\pi \times 10^{-7} \times 110 \times 10^3} = 14.5 \text{ Hz}$$

For the output circuit,

$$f_{02} = \frac{1}{2\pi C_2 (R_o + R_L)}$$

For $f_{02} \leq 100 \text{ Hz}$,

$$\frac{1}{2\pi C_2 (1 + 1) \times 10^3} \leq 100$$

$$\Rightarrow C_2 \geq \frac{1}{2\pi \times 2 \times 10^3 \times 10^2} = 0.8 \times 10^{-6}$$

Select $C_2 = 1 \times 10^{-6} = 1 \mu\text{F}$

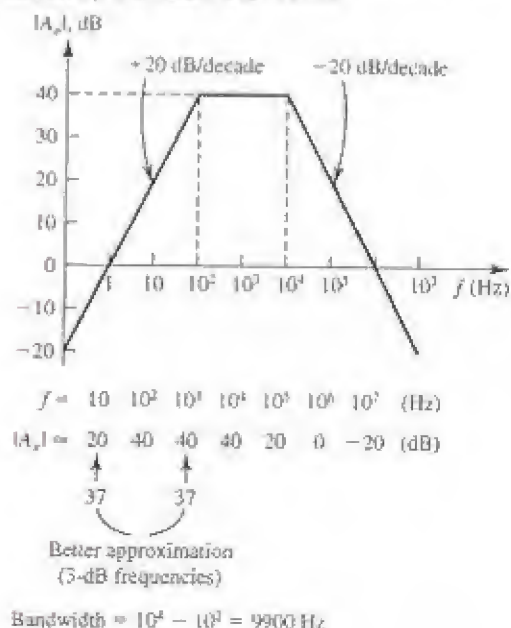
This will place the corner frequency at

$$f_{02} = \frac{1}{2\pi \times 10^{-6} \times 2 \times 10^3} = 80 \text{ Hz}$$

$$T(s) = 100 \frac{s}{\left(1 + \frac{s}{2\pi f_{01}}\right) \left(1 + \frac{s}{2\pi f_{02}}\right)}$$

1.76 The L.P factor $1/(1 + jf/10^4)$ results in a Bode plot like that in Fig. 1.23(a) with the 3 dB frequency $f_0 = 10^4 \text{ Hz}$. The high-pass factor $1/(1 + 10^4/jf)$ results in a Bode plot like that in Fig. 1.24(a) with the 3 dB frequency $f_0 = 10^4 \text{ Hz}$.

The Bode plot for the overall transfer function can be obtained by summing the dB values of the two individual plots and then raising the resulting plot vertically by 40 dB (corresponding to the factor 100 in the numerator). The result is as follows:

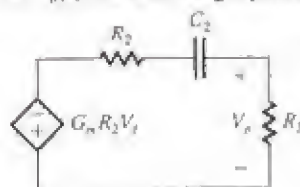


1.77

$$T_1(s) = \frac{V_1(s)}{V_i(s)} = \frac{1/sC_1}{1/sC_1 + R_1} = \frac{1}{sC_1 R_1 + 1} \quad \text{LP}$$

$$3 \text{ dB frequency} = \frac{1}{2\pi C_1 R_1} = \frac{1}{2\pi \times 10^{-11} \times 10^5} = 15.9 \text{ Hz}$$

For $T_v(s)$, the following equivalent circuit can be used:



$$T_v(s) = -G_m R_2 \frac{R_3}{R_2 + R_3 + 1/sC_2}$$

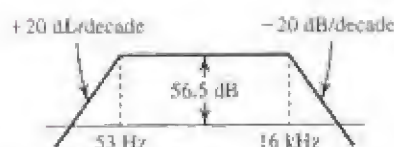
$$= -G_m (R_2 \parallel R_3) \frac{s}{s + \frac{1}{C_2(R_2 + R_3)}}$$

$$3 \text{ dB frequency} = \frac{1}{2\pi C_2(R_2 + R_3)}$$

$$= \frac{1}{2\pi \times 100 \times 10^{-9} \times 30 \times 10^3} = 53 \text{ Hz}$$

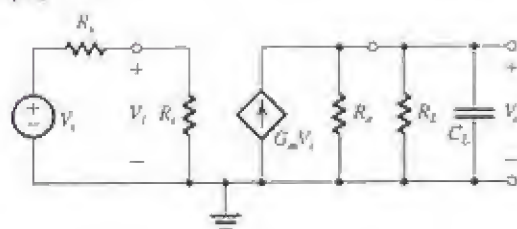
$$\therefore T(s) = T_v(s) T_a(s)$$

$$= \frac{1}{1 + \frac{s}{2\pi \times 15.9 \times 10^3}} \times -666.7 \times \frac{s}{s + (2\pi \times 53)}$$



$$\text{Bandwidth} = 16 \text{ kHz} - 53 \text{ Hz} \approx 16 \text{ kHz}$$

1.78



$$V_i = V_o \frac{R_i}{R_i + R_1} \quad (1)$$

To satisfy constraint (1), namely

$$V_i \geq \left(1 - \frac{x}{100}\right) V_o$$

We substitute in Eq.(1) to obtain

$$\frac{R_i}{R_i + R_1} \geq 1 - \frac{x}{100}$$

Thus

$$\frac{R_i + R_1}{R_i} \leq \frac{1}{1 - \frac{x}{100}}$$

$$\frac{R_i}{R_1} \leq \frac{1}{1 - \frac{x}{100}} - 1 = \frac{\frac{x}{100}}{1 - \frac{x}{100}}$$

which can be expressed as

$$\frac{R_i}{R_1} \geq \frac{1 - \frac{x}{100}}{\frac{x}{100}}$$

resulting in

$$R_i \geq R_1 \left(\frac{100}{x} - 1 \right) \quad (1)$$

The 3-dB frequency is determined by the parallel RC circuit at the output,

$$f_0 = \frac{1}{2\pi} \omega_0 = \frac{1}{2\pi} \frac{1}{C_L(R_L \parallel R_o)}$$

Thus,

$$f_0 = \frac{1}{2\pi C_L} \left(\frac{1}{R_L} + \frac{1}{R_o} \right)$$

To obtain a value for f_0 greater than a specified value f_{3dB} we select R_o so that

$$\frac{1}{2\pi C_L} \left(\frac{1}{R_L} + \frac{1}{R_o} \right) \geq f_{3dB}$$

$$\frac{1}{R_L} + \frac{1}{R_o} \geq 2\pi C_L f_{3dB}$$

$$\frac{1}{R_o} \geq 2\pi C_L f_{3dB} - \frac{1}{R_L}$$

$$R_o \leq \frac{1}{2\pi f_{3dB} C_L - \frac{1}{R_L}} \quad (2)$$

To satisfy constraint (3), we first determine the dc gain as

$$\text{dc gain} = \frac{R_i}{R_i + R_1} G_m (R_o \parallel R_L)$$

For the dc gain to be greater than a specified value A_0 ,

$$\frac{R_i}{R_i + R_1} G_m (R_o \parallel R_L) \geq A_0$$

The first factor on the LHS is (from constraint (1))

greater or equal to $(1 - x/100)$. Thus

$$G_m \geq \frac{A_0}{\left(1 - \frac{x}{100}\right)(R_o \parallel R_L)} \quad (3)$$

Substituting $R_o = 10 \text{ k}\Omega$ and $x = 20\%$ in (1) results in

$$R_L \geq 10 \left(\frac{100}{20} - 1 \right) = 40 \text{ k}\Omega$$

Substituting $f_{3dB} = 3 \text{ MHz}$, $C_L = 10 \text{ pF}$ and $R_L = 10 \text{ k}\Omega$ in Eq. (2) results in

$$R_o \leq \frac{1}{2\pi \times 3 \times 10^6 \times 10 \times 10^{-12} - \frac{1}{10^3}} = 11.3 \text{ k}\Omega$$

Substituting $A_0 = 80$, $x = 20\%$, $R_L = 10 \text{ k}\Omega$, and $R_o = 11.3 \text{ k}\Omega$, eq. (3) results in

$$G_m \geq \frac{80}{\left(1 - \frac{20}{100}\right)(10 \parallel 11.3) \times 10^3} = 18.85 \text{ mA/V}$$

If the more practical value of $R_o = 10 \text{ k}\Omega$ is used then

$$G_m \geq \frac{80}{\left(1 - \frac{20}{100}\right)(10 \parallel 10) \times 10^3} = 20 \text{ mA/V}$$

1.79 Using the voltage-divider rule we obtain

$$\frac{V_o}{V_i} = \frac{Z_2}{Z_1 + Z_2}$$

where

$$Z_1 = R_1 \parallel \frac{1}{sC_1} \quad \text{and} \quad Z_2 = R_2 \parallel \frac{1}{sC_2}$$

It is obviously more convenient to work in terms of admittances. Therefore we express V_o/V_i in the alternate form

$$\frac{V_o}{V_i} = \frac{Y_1}{Y_1 + Y_2}$$

and substitute $Y_1 = (1/R_1) + sC_1$ and $Y_2 = (1/R_2) + sC_2$ to obtain

$$\begin{aligned} \frac{V_o}{V_i} &= \frac{\frac{1}{R_1} + sC_1}{\frac{1}{R_1} + \frac{1}{R_2} + s(C_1 + C_2)} \\ &= \frac{C_1}{C_1 + C_2} \frac{s + \frac{1}{C_1 R_1}}{s + \frac{1}{(C_1 + C_2) \left(\frac{1}{R_1} + \frac{1}{R_2} \right)}} \end{aligned}$$

This transfer function will be independent of frequency (s) if the second factor reduces to unity. This in turn will happen if

$$\frac{1}{C_1 R_1} = \frac{1}{C_1 + C_2} \left(\frac{1}{R_1} + \frac{1}{R_2} \right)$$

which can be simplified as follows

$$\begin{aligned} \frac{C_1 + C_2}{C_2} &= R_1 \left(\frac{1}{R_1} + \frac{1}{R_2} \right) \\ 1 + \frac{C_2}{C_1} &= 1 + \frac{R_1}{R_2} \end{aligned} \quad (1)$$

or

$$C_1 R_1 = C_2 R_2$$

When this condition applies, the attenuator is said to be compensated, and its transfer function is given by

$$\frac{V_o}{V_i} = \frac{C_1}{C_1 + C_2}$$

which, using Eq. (1) above can be expressed in the alternate form

$$\frac{V_o}{V_i} = \frac{1}{1 + \frac{R_1}{R_2}} = \frac{R_2}{R_1 + R_2}$$

Thus when the attenuator is compensated ($C_1 R_1 = C_2 R_2$) its transmission can be determined either by its two resistors R_1 , R_2 or by its two capacitors C_1 , C_2 , and the transmission is *not* a function of frequency.

1.80 The HP STC circuit whose response determines the frequency response of the amplifier in the low-frequency range has a phase angle of 11.4° at $f = 100 \text{ Hz}$. Using the equation for $\angle T(j\omega)$ from Table 1.2 we obtain

$$\tan^{-1} \frac{f_0}{100} = 11.4^\circ \Rightarrow f_0 = 20.16 \text{ Hz.}$$

The LP STC circuit whose response determines the amplifier response at the high-frequency end has a phase angle of -11.4° at $f = 1 \text{ kHz}$. Using the relationship for $\angle T(j\omega)$ given in Table 1.2 we obtain for the LP STC circuit.

$$-\tan^{-1} \frac{10^3}{f_0} = -11.4^\circ \Rightarrow f_0 = 4959.4 \text{ Hz}$$

At $f = 100$ Hz the drop in gain is due to the HP STC network, and thus its value is

$$20 \log \frac{1}{\sqrt{1 + \left(\frac{20.16}{100}\right)^2}} = -0.17 \text{ dB}$$

Similarly, at $f = 1$ kHz the drop in gain is caused by the LP STC network. The drop in gain is

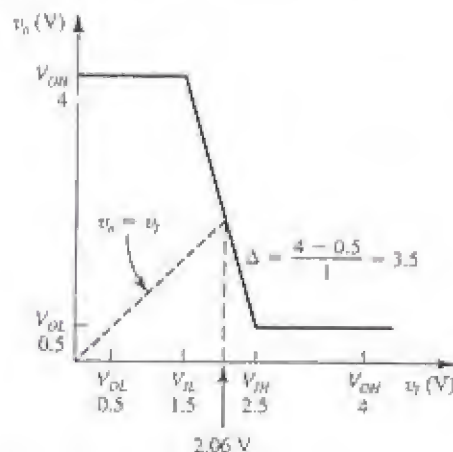
$$20 \log \frac{1}{\sqrt{1 + \left(\frac{1000}{4959.4}\right)^2}} = -0.17 \text{ dB}$$

The gain drops by 3 dB at the corner frequencies of the two STC networks, that is, at $f = 20.16$ Hz and $f = 4959.4$ Hz.

1.81 $NM_H = V_{OH} - V_{IH} = 3.3 - 1.7 = 1.6 \text{ V}$

$$NM_L = V_{IL} - V_{OL} = 1.3 - 0 = 1.3 \text{ V}$$

1.82



(a) $NM_H = V_{OH} - V_{IH} = 4 - 2.5 = 1.5 \text{ V}$

$$NM_L = V_{IL} - V_{OL} = 1.5 - 0.5 = 1 \text{ V}$$

(b) In the transition region

$$V_O = 4 - 3.5(V_I - 1.5)$$

$$= 9.25 - 3.5V_I$$

If

$$V_O = V_I \Rightarrow 4.5V_O = 9.25$$

$$V_O = V_I = 2.06 \text{ V}$$

(c) Slope = -3.5 V/V

1.83

$$NM_H = V_{OH} - V_{IH} = 0.8 V_{DD} - 0.6 V_{DD} = 0.2 V_{DD}$$

$$NM_L = V_{IL} - V_{OL} = (0.4 - 0.1) V_{DD} = 0.3 V_{DD}$$

$$\text{width of transition region} = V_{IH} - V_{IL} = 0.2 V_{DD}$$

$$\text{for a minimum } NM \text{ of } 1 \text{ V} \Rightarrow 0.2 V_{DD} = 1$$

$$V_{DD} = 5 \text{ V}$$

1.84

(a) Worst case $NM_H = V_{OH, \min} - V_{IH} = 2.4 - 2 = 0.4 \text{ V}$

Worst case $NM_L = V_{IL, \max} - V_{OL} = 0.8 - 0.4 = 0.4 \text{ V}$

(b) $P_{D_{\text{avg}}} = \frac{1}{20} [5 \times 3 + 5 \times 1] = 10 \text{ mW}$

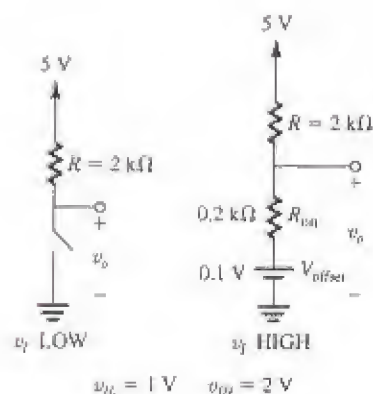
(c) Dynamic power dissipation = $f_C V_{DD}^2 \approx$

$$10^6 \times 45 \times 10^{-12} \times 25 = 1.13 \text{ mW}$$

(d) $t_p(\text{typical}) = \frac{1}{2}(t_{PHL} + t_{PLH}) = \frac{1}{2}(7 + 11) = 9 \text{ ns}$

$$t_p(\text{maximum}) = \frac{1}{2}(15 + 22) = 18.5 \text{ ns}$$

1.85



$$v_{IL} = 1 \text{ V} \quad v_{IH} = 2 \text{ V}$$

(a) $V_{OL} = \frac{5 - 0.1}{2.2} = 0.2 + 0.1 = 0.545 \text{ V}$

$$V_{OH} = 5 \text{ V}$$

$$NM_H = V_{OH} - V_{IH} = 3 \text{ V}$$

$$NM_L = V_{IL} - V_{OL} = 0.455 \text{ V}$$

(b) $V_{OH} = 5 - N(0.2 \times 10^{-3})R = 5 - 0.4N$

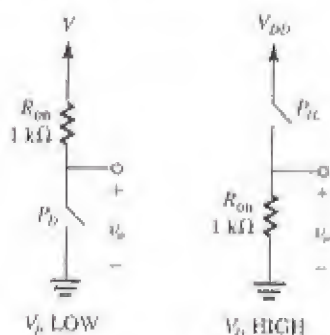
$$NM_H = 5 - 0.4N - 2 = 3 - 0.4N = 0.455 \quad \therefore N = 6$$

(c) (i) $P_{D_{V_{OL}}LOW} = (5 - 0.1)^2 / 2.2 \text{ k}\Omega = 10.9 \text{ mW}$

(ii) $P_{D_{V_{OL}}HIGH} = 5 \times (0.2 \times 6) = 6 \text{ mW}$

1.86 (a) $V_{OL} = 0$ $V_{OH} = 5$ $NM_L = V_{HL} - V_{OL} = 2.5 - 0 = 2.5 \text{ V}$

$NM_H = V_{OH} - V_{HL} = 5 - 2.5 = 2.5 \text{ V}$



(b) $V_O(t) = 0 - (0 - 5)e^{-t/R_{on}C} = 5e^{-t/R_{on}C}$

For $t_{PHL} \Rightarrow V_O(t) = 5e^{-t_{PHL}/R_{on}C} = \frac{1}{2}(5) = 2.5$

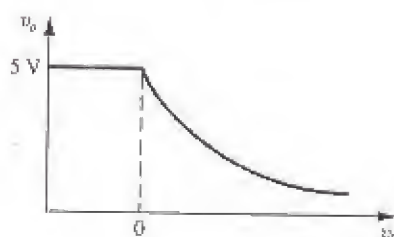
$t_{PHL} = -(10^3)(10^{-9}) \ln \frac{2.5}{5} = 0.69 \text{ ns}$

For $t_{YHL} \Rightarrow V_O(t) = 5e^{-t_{YHL}/R_{on}C} = 4.5 \text{ V}$

$t_1 = 0.01 \text{ ns}$ $V_O(t) = 5e^{-t_1/R_{on}C} = 0.5 \text{ V}$

$t_2 = 2.3 \text{ ns}$

$\therefore t_{YHL} = t_2 - t_1 = 2.2 \text{ ns}$



(c) $V_O(t) = 5 - (5 - 0)e^{-t/R_{eq}C} = 5 - 5e^{-t/R_{eq}C}$

$V_O = 5 - 5e^{-t_{PLH}/R_{eq}C} = 2.5 \text{ ns}$

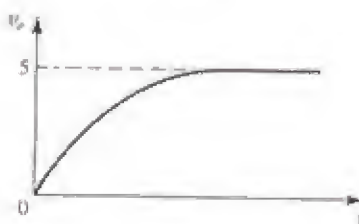
$t_{PLH} = 0.69 \text{ ns}$

For t_{TLH} ,

$V_O(t) = 5 - 5e^{-t_1/R_{eq}C} = 0.5 \Rightarrow t_1 = 0.10 \text{ ns}$

$V_O(t) = 5 - 5e^{-t_2/R_{eq}C} = 4.5 \Rightarrow t_2 = 2.3 \text{ ns}$

$t_{TLH} = 2.3 - 0.1 = 2.2 \text{ ns}$



1.87

$V_{OH} = 5 \text{ V}$

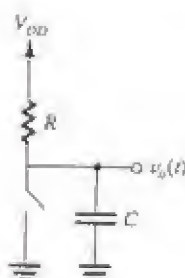
$V_{OL} = 5 - 2 \times 1 = 3 \text{ V}$

1.88 $P_{dynamic} = fCV_{DD}^2 = 100 \times 10^6 \times 10 \times 10^{-12} \times 25 = 25 \text{ mW}$

$P = V_{DD} I_{avg} = 5 I_{avg} = 25 \text{ mW}$

$I_{avg} = 5 \text{ mA}$

1.89



$v_o(t)$ begins at V_{OL} and rises toward V_{OH} (in this case $V_{OH} = V_{DD}$) according to

$$v_o(t) = v_{\infty} - (v_{\infty} - v_{(0)})e^{-t/CR}$$

$$= V_{OH} - (V_{OH} - V_{OL})e^{-t/CR}$$

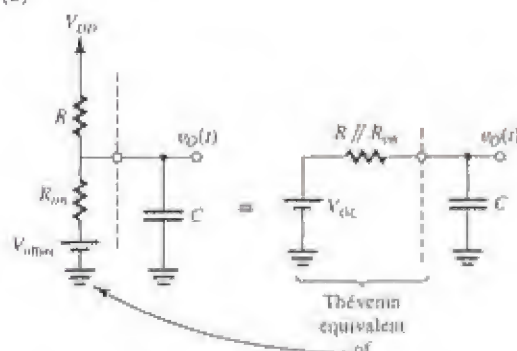
$$= V_{OH} - (V_{OH} - V_{OL})e^{-t/\tau_1}, \tau_1 = CR \quad \text{Q.E.D.}$$

$v_o(t)$ reaches $\frac{1}{2}(V_{OH} + V_{OL})$ at $t = t_{PLH}$,

$\frac{1}{2}(V_{OH} + V_{OL}) = V_{OH} - (V_{OH} - V_{OL})e^{-t_{PLH}/\tau_1}$

$\Rightarrow t_{PLH} = \tau_1 \ln 2 = 0.69CR \quad \text{Q.E.D.}$

(b)



$$V_{OL} = V_{DD} \frac{R_{on}}{R + R_{on}} + V_{offset} \frac{R}{R + R_{on}}$$

$$v_O(t) = v_{OL} - (v_{OL} - v_{OH}) e^{-t/\tau_2}, \quad \tau_2 = C(R \parallel R_{on})$$

$$= V_{OL} - (V_{OL} - V_{OH}) e^{-t/\tau_2}$$

$$= V_{OL} + (V_{OH} - V_{OL}) e^{-t/\tau_2} \quad \text{Q.E.D.}$$

$$v_O(t_{FHL}) = \frac{1}{2}(V_{OL} + V_{OH})$$

Thus,

$$t_{FHL} = \tau_2 \ln 2 = 0.69C(R \parallel R_{on})$$

$$= 0.69CR_{on}, \quad R_{on} \ll R \quad \text{Q.E.D.}$$

$$(c) \quad \tau_P = \frac{1}{2}(t_{FHL} + t_{FLH}) = \frac{1}{2} \times 0.69(CR + CR_{on})$$

$$= 0.35CR, \quad \text{for } R_{on} \ll R \quad \text{Q.E.D.}$$

(d) Static power is dissipated only when the output is low, in which case

$$P = \frac{V_{DD}^2}{R + R_{on}} \approx \frac{V_{DD}^2}{R}, \quad \text{for } R_{on} \ll R,$$

and assuming that $V_{offset} \ll V_{DD}$. Thus if the inverter spends only half the time in this low-output state,

$$P = \frac{1}{2} \frac{V_{DD}^2}{R}$$

(e) Large R results in low P but high τ_P and vice-versa. For $V_{DD} = 5$ V and $C = 10$ pF,

$$\bullet \quad \tau_P \leq 10 \text{ ns} \Rightarrow 0.35CR \leq 10 \text{ ns} \\ \Rightarrow R \leq 2875 \Omega$$

$$\bullet \quad P \leq 10 \text{ mW} \Rightarrow \frac{1}{2} \times \frac{25}{R} \leq 10 \times 10^{-3} \\ \Rightarrow R \geq 1250 \Omega$$

Thus,

$$1250 \leq R \leq 2875 \Omega$$

Selecting $R = 2 \text{ k}\Omega$,

$$\tau_P = 0.35 \times 10 \times 10^{-12} \times 2 \times 10^3 = 7 \text{ ns}$$

$$P = \frac{1}{2} \times \frac{25}{2} = 6.25 \text{ mW}$$

Unnumbered 1.48

$$\frac{v_{i1}}{v_i} = 0.5, \quad \frac{v_{i2}}{v_{i1}} = 100 \frac{1000}{100} \approx 100$$

$$\frac{v_{i2}}{v_i} = 10 \times \frac{10}{11} = 9.09$$

$$\frac{v_o}{v_i} = \frac{10}{11} = 0.909$$

$$A_o \approx 826.3$$

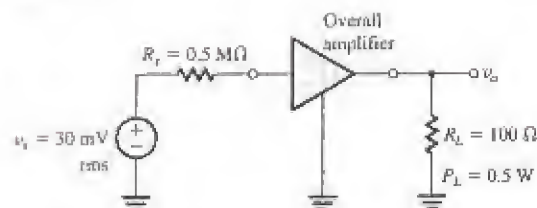
$$\frac{v_o}{v_i} = 413.1$$

$$0.5 \times 100 \times 10 \times \frac{10}{11} = 450$$

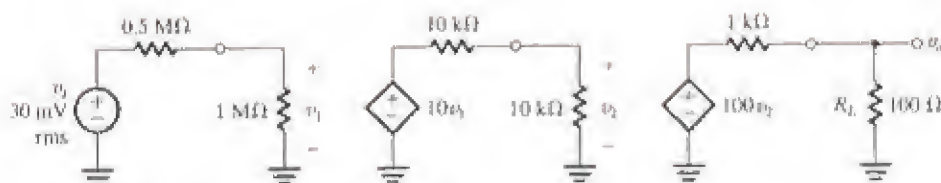
$$P_L = 0.5 \text{ W} = v_o^2/R_L$$

$$v_o = \sqrt{0.5 \times 100} = 7.07 \text{ V}$$

Unnumbered 1.50

Required overall voltage gain $= 7.07/0.03 = 235.7 = 235 \text{ V/V}$.

In order to avoid the loss of more than 2/3 of the signal strength in coupling the source to the first stage of the amplifier, we have use the type (1), high-input resistance amplifier as the input stage. Both type 2 and type 3 do not satisfy this requirement. The type (1) amplifier has an open-circuit voltage gain of 10 and thus connect by itself satisfy the overall gain requirement.



We next consider cascading the type (1) input stage with the type (2), high-gain stages. The result would be

Overall voltage gain

$$= \frac{1}{1+0.5} \times 10 \times \frac{10}{10+10} \times 100 \times \frac{100}{100+1000}$$

$$= 30.3 \text{ V/V}$$

Thus, this cascade amplifier does not meet specs. The reason is obvious from the gain calculation: the output resistance, 1 kΩ, is too high for feeding a load of 100 Ω and indeed results in a loss of gain by a factor of 11!

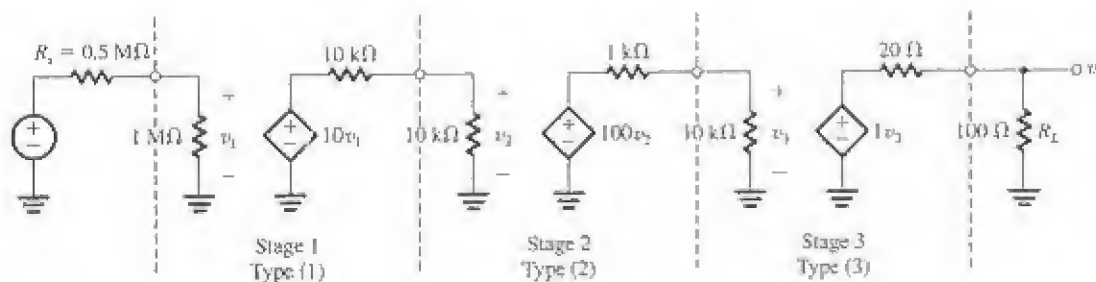
That's where the type (3) amplifier stage can be beneficial. While its open-circuit gain is only 1, its output resistance is 20 Ω, five times lower than the 100 Ω load. The overall amplifier would then look as follows:

Overall voltage gain $\approx \frac{v_o}{v_i}$

$$= \frac{1}{1+0.5} \times 10 \times \frac{10}{10+10} \times 100 \times \frac{10}{10+1} \times 1 \times \frac{100}{100+20}$$

$$= 252.5 \text{ V/V}$$

which meets the specified gain of 235 V/V.



Chapter 2 - Problems

2.1

The minimum number of pins required by dual-op-amp is 8. Each op-amp has 2 input terminals (4 pins) and one output terminal (2 pins). Another 2 pins are required for power.

Similarly, the minimum number of pins required by quad-opamp is 14:

$$4 \times 2 + 4 \times 1 + 2 = 14$$

2.2

Refer to Fig. P2.2. $V_+ = V_- = \frac{1K\Omega}{1K\Omega + 1K\Omega} = \frac{4}{1001} V$
 $V_o = A V_+ \Rightarrow A = \frac{V_o}{V_+} = \frac{4}{4/1001} = 1001$

2.3

The voltage at the positive input has to be $-3.000V$.

$$V_+ = -3.020V, A = \frac{V_o}{(V_+ - V_-)} = \frac{-2}{-3.020 - (-3)} = 100$$

2.4

#	V_1	V_2	$\frac{V_d}{V_2 - V_1}$	V_o	V_o/V_d
1	0.00	0.00	0.00	0.00	-
2	1.00	1.00	0.00	0.00	-
3	⊖	1.00	ⓐ	1.00	
4	1.00	1.10	0.10	10.1	101
5	2.01	2.00	-0.01	-0.99	99
6	1.99	2.00	0.01	1.00	100
7	5.10	ⓑ	ⓓ	-5.10	

experiments 4, 5, 6 show that the gain is

approximately 100 V/V. The missing entry for experiment #3 can be predicted as follows:

$$\textcircled{b} V_d = \frac{V_2}{A} = \frac{1.00}{100} = 0.01V$$

$$\textcircled{c} V_1 = V_2 - V_d = 1.00 - 0.01 = 0.99V$$

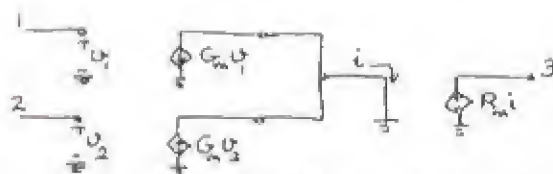
The missing entries for experiment #7:

$$\textcircled{d} V_d = \frac{-5.10}{100} = -0.051V$$

$$\textcircled{e} V_2 = V_1 + V_d = 5.10 - 0.051 = 5.049V$$

All the results seem to be reasonable.

2.5



$$A = G_m R_m = 100 \times 10^{-3} \times 10^6 = 100,000 \text{ V/V}$$

2.6

$$V_{CM} = 1V \sin(2\pi 60)t = \frac{1}{2}(V_1 + V_2)$$

$$V_d = 0.01 \sin(2\pi 1000)t = V_1 - V_2$$

$$V_1 = V_{CM} - V_d/2 = \sin(120\pi t) - 0.005 \sin(2000\pi t)$$

$$V_2 = V_{CM} + V_d/2 = \sin(120\pi t) + 0.005 \sin(2000\pi t)$$

2.7

$$V_d = R(G_{m2}V_2 - G_{m1}V_1) \text{ Refer to Fig. 2.4.}$$

$$V_o = V_d = \mu V_d = \mu R(G_{m2}V_2 - G_{m1}V_1)$$

$$V_o = \mu R(G_m V_2 + \frac{1}{2} \Delta G_m V_2 - G_m V_1 + \frac{1}{2} \Delta G_m V_1)$$

$$V_o = \mu R G_m \underbrace{(V_2 - V_1)}_{V_d} + \frac{1}{2} \mu R \Delta G_m \underbrace{(V_1 + V_2)}_{2V_{CM}}$$

$$\text{we have } V_o = A_d V_d + A_{CM} V_{CM}$$

$$\Rightarrow A_d = \mu R G_m, A_{CM} = \mu R \Delta G_m$$

$$CMRR = 20 \log \left| \frac{A_d}{A_{CM}} \right| = 20 \log \frac{G_m}{\Delta G_m}$$

cont.

$$20 \log_{10} A_d = 80 \text{ dB} \Rightarrow A_d = 10^4$$

$$\frac{A_{cm}}{A_d} = \frac{\Delta G_m}{G_m} \Rightarrow A_{cm} = 10^4 \times \frac{0.1}{100} = 10$$

$$\text{CMRR} = 20 \log \frac{G_m}{\Delta G_m} = 20 \log \frac{1}{0.1/100} = 60$$

2.8

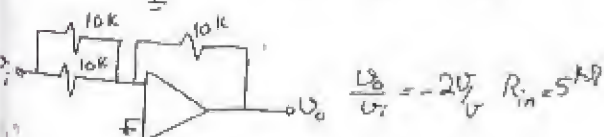
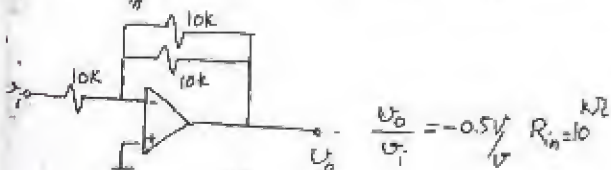
circuit	v_o/v_i (V/V)	R_{in} (k Ω)	
a	$\frac{-100}{10} = -10$	10	
b	-10	10	
c	-10	10	virtual ground
d	-10	10	no current in 10k Ω

2.9

closed loop gain = -1 V/V . For $v_i = 5 \text{ V} \Rightarrow v_o = -5 \text{ V}$
 Gain would be in the range of $\frac{-0.95}{1.05}$ to $\frac{-1.05}{0.95}$: $-0.9 < G < -1.1$
 for $v_i = 5 \Rightarrow -4.5 \text{ V} < v_o < -5.5 \text{ V}$

2.10

There are four possibilities:



2.11

a. $G = 1 \text{ V/V}$

c. $G = 0.1 \text{ V/V}$

e. $G = 10 \text{ V/V}$

b. $G = 10 \text{ V/V}$

d. $G = 100 \text{ V/V}$

2.12

a. $G = -1 \text{ V/V} = -\frac{R_2}{R_1} \Rightarrow R_1 = R_2 = 10 \text{ k}\Omega$

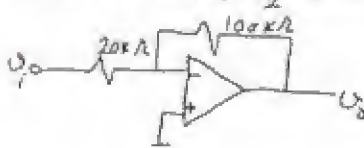
b. $G = -2 \text{ V/V} = -\frac{R_2}{R_1} \Rightarrow R_1 = 10 \text{ k}\Omega, R_2 = 20 \text{ k}\Omega$

c. $G = -0.5 \text{ V/V} = -\frac{R_2}{R_1} \Rightarrow R_1 = 20 \text{ k}\Omega, R_2 = 10 \text{ k}\Omega$

d. $G = -100 \text{ V/V} = -\frac{R_2}{R_1} \Rightarrow R_1 = 10 \text{ k}\Omega, R_2 = 1 \text{ M}\Omega$

2.13

$\frac{v_o}{v_i} = -5 = -\frac{R_2}{R_1} \Rightarrow R_2 = 5R_1$
 $R_1 + R_2 = 120 \text{ k}\Omega \Rightarrow 5R_1 + R_1 = 120 \text{ k}\Omega \Rightarrow R_1 = 20 \text{ k}\Omega \Rightarrow R_2 = 100 \text{ k}\Omega$



2.14

$20 \log |G| = 26 \text{ dB} \Rightarrow G = 19.95 \text{ V/V} = \frac{v_o}{v_i} = -\frac{R_2}{R_1}$
 $\Rightarrow R_2 = 19.95 R_1 \leq 10 \text{ M}\Omega$

For largest possible input resistance, select $R_2 = 10 \text{ M}\Omega \Rightarrow R_1 \approx 500 \text{ k}\Omega$
 $R_{in} = 500 \text{ k}\Omega$

2.15

$G = \frac{v_o}{v_i} = -\frac{R_2}{R_1} = -\frac{100}{10} = -10$

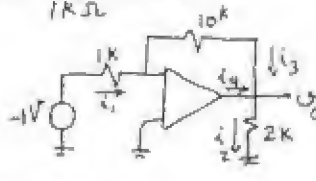
$v_{low} = -10 \text{ V}, v_{high} = 0, v_{avg} = -5 \text{ V}$

2.16

$$\frac{V_o}{V_i} = -\frac{R_2}{R_1} \Rightarrow V_o = -1 \times \frac{10k\Omega}{1k\Omega} = -10V$$

$$i_2 = \frac{V_o}{2k\Omega} = 5mA$$

$$i_1 = i_3 = \frac{V_o}{10k\Omega} = 1mA$$



$$i_4 + i_2 - i_3 = 4mA \quad \text{This additional current comes from the output of the op-amp.}$$

2.17

$$|Gain| = \frac{R_2}{R_1} = \frac{R_2 (1 + \frac{x}{100})}{R_1 (1 + \frac{x}{100})} \approx \frac{R_2}{R_1} (1 \pm \frac{2x}{100})$$

$\Rightarrow 2x\%$ is the tolerance on the closed loop gain (G).

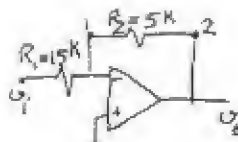
$$G = -100V/V, x = 5 \Rightarrow -110 < G < -90$$

$$\text{or more precisely: } -100 \frac{105}{95} < G < -100 \frac{95}{105}$$

$$-110.5 < G < -90.5$$

2.18

$$G = \frac{V_o}{V_i} = -\frac{R_2}{R_1} \Rightarrow \frac{R_2}{R_1} = \frac{5}{15}$$



$$V_i = 0V, V_o = V_o = 5V$$

$$\text{For } \pm 1\% \text{ on } R_1, R_2: R_1 = 15 \pm 0.15k\Omega, R_2 = 5 \pm 0.05k\Omega$$

$$V_o = V_i \frac{R_2}{R_1} = 15 \frac{R_2}{R_1} \Rightarrow 15 \frac{4.95}{15.15} < V_o < 15 \frac{5.05}{14.85}$$

$$\Rightarrow 4.9V < V_o < 5.1V$$

$$\text{For } V_i = -15 \pm 0.15V \quad 14.85 \frac{4.95}{15.15} < V_o < 15.15 \frac{5.05}{14.85}$$

$$\Rightarrow 4.85V < V_o < 5.15V$$

2.19

$$V_i = -\frac{V_o}{A} = -\frac{V_o}{200}$$

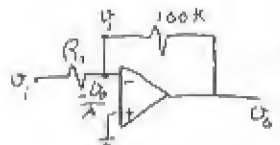
$$\frac{V_o}{V_i} = -50V/V$$

$$\frac{V_i - (-\frac{V_o}{A})}{R_1} = \left(\frac{-\frac{V_o}{A} - V_o}{100k\Omega} \right) \Rightarrow R_1 = 100k\Omega \times \frac{\frac{V_o}{200} - \frac{V_o}{50}}{\frac{-V_o}{200} - V_o}$$

$$\Rightarrow R_1 = 100k\Omega \times \frac{3}{201} = 1.49k\Omega$$

$$\text{shunt Resistor } R_a: R_a \parallel 2k\Omega = 1.49k\Omega$$

$$\frac{R_a \times 2}{R_a + 2} = 1.49 \Rightarrow R_a = 5.54k\Omega$$



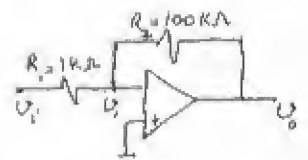
2.20

a)

$$\frac{V_o}{V_i} = -\frac{R_2}{R_1} \Rightarrow -100V/V = -\frac{R_2}{1k\Omega} \Rightarrow R_2 = 100k\Omega$$

b) $A = 1000V/V$

$$V_i = -\frac{V_o}{A}$$



$$\frac{V_i - V_i}{R_1} = \frac{V_i - V_o}{R_2}$$

$$\frac{V_o}{V_i} = \frac{-R_2/R_1}{1 + (1 + \frac{R_2}{R_1})/A} = \frac{-100}{1 + \frac{101}{1000}} = -90.8V/V$$

$$\Rightarrow \frac{V_o}{V_i} = 90.8V/V$$

c) Assume $R'_1 = R_x \parallel R_1$ when $R_1 = 1k\Omega$

$$\frac{V_o}{V_i} = 100V/V$$

$$\frac{V_i - V_i}{R'_1} = \frac{V_i - V_o}{R_2} \Rightarrow R'_1 = R_2 \times \left(\frac{-V_o}{100} - \frac{-V_o}{1000} \right) / \left(\frac{-V_o}{1000} - 0 \right)$$

$$R'_1 = \frac{1-0.1}{1.001} = 0.899k\Omega = \frac{R_1 R_x}{R_1 + R_x} = \frac{R_x}{1 + R_x}$$

$$\Rightarrow R_x = 8.9k\Omega \approx 8.87k\Omega \pm 1\%$$

2.21

Voltage of the inverting input terminal

Cont.

will vary from $\frac{-10V}{1000}$ to $\frac{+10V}{1000}$. Thus the virtual ground will depart from the ideal voltage of zero by a maximum of $\pm 10mV$.

2.22

a) For $A = \infty$: $V_i = 0$

$$V_o = -i_i R_F$$

$$R_m = \frac{V_o}{i_i} = -R_F$$

$$R_{ia} = \frac{V_i}{i_i} = 0$$



b) For $A = \text{finite}$: $V_i = -\frac{V_o}{A}$, $V_o = V_i - i_i R_F$

$$\Rightarrow V_o = -\frac{V_o}{A} - i_i R_F \Rightarrow R_m = \frac{V_o}{i_i} = -\frac{R_F}{1 + \frac{1}{A}}$$

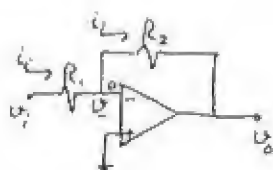
$$R_i = \frac{V_i}{i_i} = \frac{R_F}{1+A} \quad R_i = \frac{V_i}{i_i} = \frac{-V_o/A}{i_i} = \frac{-V_o/A}{\frac{V_o}{-R_m}} = \frac{R_m}{A} = \frac{-R_F}{A(1+A)}$$

2.23

$$V_o = -AV_- = V_- - i_i R_2$$

$$i_i R_2 = (1+A)V_-$$

$$V_- = \frac{i_i R_2}{1+A}$$



$$\text{Now: } V_i = i_i R_1 + V_- = i_i R_1 + \frac{i_i R_2}{1+A}$$

$$R_m = \frac{V_i}{i_i} = R_1 + \frac{R_2}{1+A}$$

2.24

$$G = \frac{-R_2/R_1}{1 + \frac{1 + R_2/R_1}{A}}$$

$$\text{Gain Error } \epsilon = \left(1 + \frac{R_2/R_1}{A}\right) \times 100$$

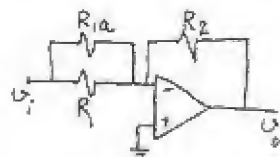
$$\epsilon = \begin{matrix} 0.1\% \\ A \end{matrix} \quad \begin{matrix} 1\% \\ 1000(1 + \frac{R_2}{R_1}) \end{matrix}$$

$$\begin{matrix} 1\% \\ 100(1 + \frac{R_2}{R_1}) \end{matrix}$$

$$\begin{matrix} 10\% \\ 10(1 + \frac{R_2}{R_1}) \end{matrix}$$

Gain with R_{ia} :

$$G = \frac{\frac{R_2}{R_1} (1 + \frac{R_1}{R_{ia}})}{1 + \frac{1 + R_2/R_1}{A}}$$



where we have neglected the effect of R_{ia} on

the error on the denominator. To restore the gain to its nominal value of R_2/R_1 we use:

$$\frac{R_2}{R_{ia}} = \frac{1 + R_2/R_1}{A} = \frac{\epsilon}{100} \Rightarrow R_{ia} = \frac{100 R_1}{\epsilon}$$

$$\epsilon = \begin{matrix} 0.1\% \\ R_{ia} \end{matrix} \quad \begin{matrix} 1\% \\ 1000 R_1 \end{matrix} \quad \begin{matrix} 10\% \\ 10 R_1 \end{matrix}$$

2.25

$$R_i' = R_1 \parallel R_2 \quad G' = \frac{-R_2/R_i'}{1 + \frac{1 + R_2/R_i'}{A}}$$

$$G = -\frac{R_2}{R_1}$$

$$\text{In order for } G' = G: \quad G = \frac{-R_2/R_i'}{1 + \frac{1 + R_2/R_i'}{A}} = \frac{-R_2}{R_1}$$

$$R_i' = \frac{R_1 R_2}{R_1 + R_2}$$

$$\Rightarrow \frac{R_1 + R_2}{R_1 R_2} = \frac{1}{R_i'} \left(1 + \frac{1 + R_2(R_1 + R_2)}{R_1 R_2 A}\right)$$

$$(R_1 + R_2) A = A R_2 + R_2 + \frac{R_2}{R_1} (R_1 + R_2)$$

$$R_1 A = R_2 + G R_1 + G R_2$$

$$\frac{R_2}{R_1} = \frac{A - G}{1 + G}$$

2.26

$$G = \frac{-R_2/R_1}{1 + \frac{1 + R_2/R_1}{A}}$$

$$G_{\text{nominal}} = -\frac{R_2}{R_1}$$

$$\epsilon = \left| \frac{G - G_{\text{nominal}}}{G_{\text{nominal}}} \right| = \left| \frac{G}{G_{\text{nominal}}} - 1 \right|$$

$$\epsilon = \left| \frac{1}{1 + \frac{1 + R_2/R_1}{A}} - 1 \right| = \left| \frac{-\frac{1 + R_2/R_1}{A}}{1 + \frac{1 + R_2/R_1}{A}} \right| = \frac{1}{\frac{A}{1 + R_2/R_1} + 1}$$

which can be rearranged to yield:

$$\frac{A}{1 + \frac{R_2}{R_1}} + 1 = \frac{1}{\epsilon} \Rightarrow A = \left(1 + \frac{R_2}{R_1}\right) \left(\frac{1}{\epsilon} - 1\right)$$

$$\text{or } A = (1 - G_{\text{nominal}}) \left(\frac{1}{\epsilon} - 1\right)$$

For $G_{\text{nominal}} = -100 \text{ V/V}$ and $\epsilon = 10\% = 0.1$

$$A = (1 + 100) \left(\frac{1}{0.1} - 1\right) = 909 \text{ V/V}$$

This is the minimum required value for A .

2.27

$$|G| = \frac{R_2/R_1}{1 + \frac{1 + R_2/R_1}{A}} \quad A \rightarrow A(1 - \frac{x}{100})$$

$$|G'| = \frac{R_2/R_1}{1 + \frac{1 + R_2/R_1}{A(1 - \frac{x}{100})}}$$

$$\text{For } |G'| = |G| (1 - \frac{x}{100})$$

$$\frac{R_2/R_1}{1 + \frac{1 + R_2/R_1}{A(1 - \frac{x}{100})}} = \frac{R_2/R_1}{1 + \frac{1 + R_2/R_1}{A}} (1 - \frac{x}{100})$$

$$1 + \frac{1 + R_2/R_1}{A(1 - \frac{x}{100})} = (1 + \frac{1 + R_2/R_1}{A}) (1 - \frac{x}{100})$$

$$1 - \frac{x}{100} + \frac{1 + R_2/R_1}{A} \frac{1 - x/100}{1 - x/100} = 1 + \frac{1 + R_2/R_1}{A}$$

$$\frac{1 + R_2/R_1}{A} \frac{1 - x/100}{1 - x/100} - 1 + x/100 = \frac{x}{100}$$

$$A = \frac{1 + K}{1 - \frac{x}{100}} (1 + R_2/R_1) = (\frac{K-1}{1 - \frac{x}{100}}) (1 + \frac{R_2}{R_1})$$

$$\text{For } \frac{R_2}{R_1} = 100 \quad x = 50 \quad K = 100: A = \frac{99}{0.5} \times 101 = 19998$$

$$A \approx 2 \times 10^4 \text{ V/V}$$

Thus for $A = 2 \times 10^4 \text{ V/V}$, a reduction of 50% results in only 0.5% reduction of the closed loop gain whose nominal value is $\frac{R_2}{R_1} (100)$.

2.28

From the results of example 2.2, the gain of the circuit in Fig. 2.8 is given by:

$$\frac{V_o}{V_i} = -\frac{R_2}{R_1} (1 + \frac{R_4}{R_2} + \frac{R_4}{R_3})$$

$$\text{For } R_1 = R_2 = R_4 = 1 \text{ M}\Omega \Rightarrow \frac{V_o}{V_i} = -(1 + 1 + \frac{1}{R_3})$$

$$\text{a) } \frac{V_o}{V_i} = -10 \text{ V/V} \Rightarrow 10 = 2 + \frac{1}{R_3} \Rightarrow R_3 = \frac{1}{8} \text{ M}\Omega = 125 \text{ k}\Omega$$

$$\text{b) } \frac{V_o}{V_i} = -100 \text{ V/V} \Rightarrow 100 = 2 + \frac{1}{R_3} \Rightarrow R_3 = \frac{1}{98} \text{ M}\Omega = 10.2 \text{ k}\Omega$$

$$\text{c) } \frac{V_o}{V_i} = -2 \text{ V/V} \Rightarrow 2 = 2 + \frac{1}{R_3} \Rightarrow R_3 = \infty; \text{ eliminate } R_3.$$

2.29

$$R_2/R_1 = 1000, R_2 = 100 \text{ k}\Omega \Rightarrow R_1 = 100 \Omega$$

$$\text{a) } R_{in} = R_1 = 100 \Omega$$

$$\text{b) } \frac{V_o}{V_i} = -\frac{R_2}{R_1} (1 + \frac{R_4}{R_2} + \frac{R_4}{R_3}) = -1000$$

$$\text{If } R_2 = R_1 = R_4 = 100 \text{ k}\Omega \Rightarrow R_3 = \frac{100 \text{ k}\Omega}{1000 - 2} \approx 100 \Omega$$

$$R_{in} = R_1 = 100 \text{ k}\Omega$$

2.30

$$V_x = 0 - i_1 R_2, \quad i_1 = \frac{V_i}{R_1} \Rightarrow V_x = -V_i \frac{R_2}{R_1}$$

$$\frac{V_x}{V_i} = -\frac{R_2}{R_1}$$

$$V_x = V_o \frac{R_2 \parallel R_3}{R_2 \parallel R_3 + R_4} = V_o \frac{R_2 R_3}{R_2 R_3 + R_4 R_2 + R_4 R_3}$$

$$\frac{V_o}{V_x} = \frac{R_2 R_3 + R_2 R_4 + R_3 R_4}{R_2 R_3} = 1 + \frac{R_4}{R_3} + \frac{R_4}{R_2}$$

$$\frac{V_o/V_x}{V_i/V_x} = \frac{V_o}{V_i} = \frac{(1 + R_4/R_3 + R_4/R_2)}{-R_1/R_2} \Rightarrow$$

$$\frac{V_o}{V_i} = -\frac{R_2}{R_1} (1 + \frac{R_4}{R_3} + \frac{R_4}{R_2})$$

2.31

$$\text{a) } R_1 = R$$

$$R_2 = R \parallel R + \frac{R}{2} = \frac{R}{2} + \frac{R}{2} = R$$

$$R_3 = R_2 \parallel R + \frac{R}{2} = R \parallel R + \frac{R}{2} = R$$

$$R_4 = R_3 \parallel R + \frac{R}{2} = R \parallel R + \frac{R}{2} = R$$

$$\text{b) } V_o R I = R I_1 \Rightarrow I_1 = I$$

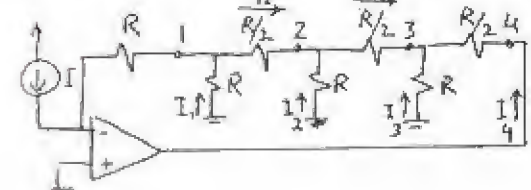
$$I_{12} = I + I = 2I \Rightarrow V_1 + 2I \frac{R}{2} = R I_2$$

$$R I + R I = R I_2 \Rightarrow I_2 = 2I$$

$$I_3 = I_2 + I_{12} = 4I \Rightarrow V_2 + 4I \frac{R}{2} = R I_3$$

$$R \times 2I + 4I \times \frac{R}{2} = R I_3 \Rightarrow I_3 = 4I, \quad I_4 = (4I + 4I)$$

$$I_4 = 8I$$



Cont.

$$c) V_1 = I_1 R = IR$$

$$V_2 = I_2 R = 2IR$$

$$V_3 = -I_3 R = -4IR$$

$$V_4 = -I_3 R + I_4 \frac{R}{2} = -4IR - 8I \frac{R}{2} = -8IR$$

2.34

$R_2 \gg R_3$, if we ignore the current across

$$R_2 : V_A = \frac{V_0 R_3}{R_3 + R_4}$$

$$\frac{V_I}{R_1} = \frac{0 - V_A}{R_2} \Rightarrow V_A = -\frac{R_2 V_I}{R_1}$$

$$V_0 \frac{R_3}{R_3 + R_4} = -\frac{R_2}{R_1} V_I \Rightarrow \frac{V_0}{V_I} = -\frac{R_2}{R_1} \left(1 + \frac{R_4}{R_3}\right)$$

Now if we recalculate V_A considering that there is a voltage divider between R_4 and

$R_3 \parallel R_2$:

$$V_A = V_0 \frac{R_3 \parallel R_2}{R_4 + R_3 \parallel R_2} = V_0 \frac{R_3 R_2}{R_4(R_3 + R_2) + R_3 R_2}$$

$$V_A = V_0 \frac{R_2 R_3}{R_4 R_3 + R_3 R_2 + R_2 R_3}$$

$$V_A = V_0 \frac{1}{R_4/R_2 + R_4/R_3 + 1}$$

$$V_A = -\frac{R_2}{R_1} V_I \Rightarrow \frac{V_0}{V_I} = -\frac{R_2}{R_1} \left(\frac{R_4}{R_2} + \frac{R_4}{R_3} + 1\right)$$

same as example 2.2.

2.32

$$a) I_1 = \frac{1V}{10k\Omega} = 0.1mA$$

$$I_2 = I_1 = 0.1mA, I_2 \times 10k\Omega = I_3 \times 100\Omega \Rightarrow I_3 = 10mA$$

$$V_X = 10mA \times 100\Omega = 1V$$

$$b) V_X = R_L I_L + V_0, I_L = I_2 + I_3 = 10.1mA$$

$$1V = R_L \times 10.1mA + V_0$$

$$R_L = \frac{1 - V_0}{10.1} \Rightarrow R_{Lmax} = \frac{1 - V_{0min}}{10.1} = \frac{14}{10.1}$$

$$c) 100\Omega \leq R_L \leq 1k\Omega$$

I_L stays fixed at 10.1mA

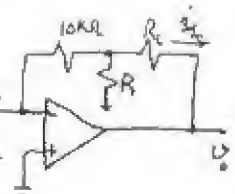
$$V_0 = V_X - R_L I_L = 1 - R_L \times 10.1 \Rightarrow -9.1V \leq V_0 \leq -0.01V$$

2.33

$$a) \frac{i_L}{i_I} = 20 \Rightarrow i_L = 20i_I$$

$$-10k\Omega \times i_I = R(i_I - i_L)$$

$$R = \frac{10k\Omega \times i_I}{20i_I - i_I} = 0.53k\Omega$$



$$b) R_L = 1k\Omega, -12V \leq V_0 \leq 12V$$

$$V_0 = R_L i_L + 10k\Omega \times i_I = i_I (1k\Omega \times 20 + 10k\Omega)$$

$$V_0 = i_I (1 \times 20 + 10) = 30i_I$$

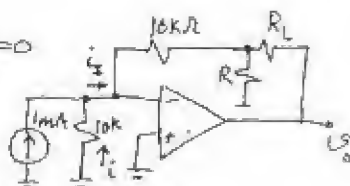
$$i_I = \frac{V_0}{30} \Rightarrow \frac{-12}{30} \leq i_I \leq \frac{12}{30} \Rightarrow -0.4mA \leq i_I \leq 0.4mA$$

$$c) R_I = \frac{V_I}{i_I} = \frac{0}{i_I} = 0$$

$$V_0 = 0 \Rightarrow i_I = 0$$

$$\Rightarrow i_L = 1mA$$

$$\text{From part a: } i_L = 20i_I = 20mA$$



2.35

$$R_I = 100k\Omega, -10 \leq \frac{V_0}{V_I} \leq -1 \frac{V}{V}$$

$$R_I = R_1 = 100k\Omega$$

$$\frac{V_0}{V_I} = -\frac{R_2}{R_1} \left(\frac{R_4}{R_3} + \frac{R_4}{R_2} + 1\right)$$

$$R_4 = 0 \Rightarrow \frac{V_0}{V_I} = -\frac{R_2}{R_1} = -1 \Rightarrow R_2 = 100k\Omega$$

$$R_4 = 10k\Omega \Rightarrow \frac{V_0}{V_I} = -10 = -1 \times \left(\frac{10k\Omega}{R_3} + \frac{10k\Omega}{100k\Omega} + 1\right)$$

$$-10 = \left(\frac{10}{R_3} + 1.1\right) \Rightarrow R_3 = 1.12k\Omega$$

$$\text{Potentiometer in the middle: } \frac{V_0}{V_I} = -1 \left(\frac{5}{5+R_3} + \frac{5}{100}\right)$$

$$\frac{V_0}{V_I} = -1.87V/V$$

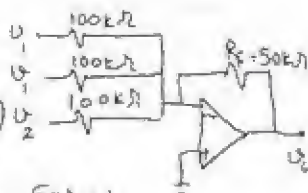
2.36

According to eq. 2.7:

$$U_o = -\left(\frac{R_F}{R_1} U_1 + \frac{R_F}{R_2} U_2 + \frac{R_F}{R_3} U_3\right)$$

$$U_o = -\left(\frac{50k}{100k} U_1 + \frac{50k}{100k} U_2 + \frac{50k}{100k} U_3\right)$$

$$U_o = -(U_1 + \frac{U_2}{2}) \quad U_1 = 3, U_2 = -3 \Rightarrow U_o = -1.5V$$



2.37

we choose the weighted summer configuration

$$U_o = -\left[4U_1 + \frac{U_2}{3}\right]$$

$$i_1 = \frac{U_1}{R_1} \quad i_2 = \frac{U_2}{R_2}$$

$$i_1, i_2 \leq 0.1 \text{ mA for } U_1, U_2 = 1V$$

$$R_1, R_2 \geq 10k\Omega$$

$$\frac{R_F}{R_1} = 4, \text{ if } R_1 = 10k\Omega \Rightarrow R_F = 40k\Omega$$

$$\frac{R_F}{R_2} = \frac{1}{3} \Rightarrow R_2 = 120k\Omega$$



2.38

$$U_o = -(2U_1 + 4U_2 + 8U_3)$$

$$R_1, R_2, R_3 \geq 10k\Omega$$

$$\frac{R_F}{R_1} = 2, \frac{R_F}{R_2} = 4, \frac{R_F}{R_3} = 8$$

$$R_3 = 10k\Omega \Rightarrow R_F = 80k\Omega$$

$$R_2 = 20k\Omega$$

$$R_1 = 40k\Omega$$

2.39

$$a) U_o = -(U_1 + 2U_2 + 3U_3)$$

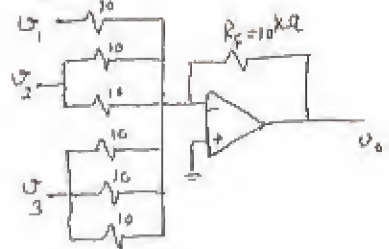
$$\frac{R_F}{R_1} = 1 \Rightarrow R_1 = 10k\Omega, \frac{R_F}{R_2} = 2 \Rightarrow R_2 = 5k\Omega$$

$$\frac{R_F}{R_3} = 3 \Rightarrow R_3 = \frac{10}{3}k\Omega$$

$$R_{I1} = 10k\Omega$$

$$R_{I2} = 5k\Omega$$

$$R_{I3} = 3.3k\Omega$$



$$b) U_o = -(U_1 + U_2 + 2U_3 + 2U_4)$$

$$\frac{R_F}{R_1} = 1 \Rightarrow R_1 = 10k\Omega$$

$$\frac{R_F}{R_2} = 1 \Rightarrow R_2 = 10k\Omega$$

$$\frac{R_F}{R_3} = 2 \Rightarrow R_3 = \frac{10}{2}k\Omega$$

$$\frac{R_F}{R_4} = 2 \Rightarrow R_4 = \frac{10}{2}k\Omega$$

$$R_{I1} = R_{I2} = 10k\Omega$$

$$R_{I3} = R_{I4} = 5k\Omega$$

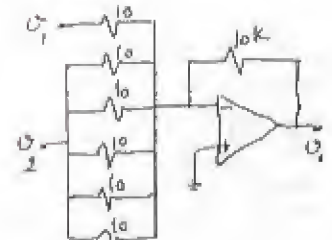
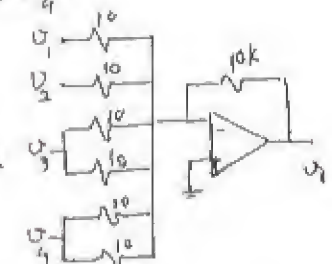
$$c) U_o = -(U_1 + 5U_2)$$

$$R_1 = 10k\Omega$$

$$R_2 = \frac{10k}{5}$$

$$R_{I1} = 10k\Omega$$

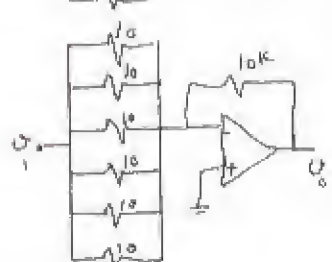
$$R_{I2} = 2k\Omega$$



$$d) U_o = -6U_1$$

$$R_1 = \frac{10k}{6}$$

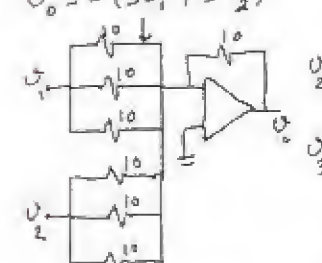
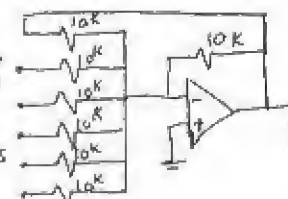
$$R_{I1} = 1.67k\Omega$$



suggested configurations:

$$U_o = -(2U_1 + 2U_2 + 2U_3)$$

$$U_o = -(3U_1 + 3U_2)$$

In order to have coefficient = 0.5, connect one of the input resistors to U_o . $\frac{U_o}{U_1} = 0.5$ 

2.40

The output signal should be:

$$V_o = -5 \sin \omega t - 5$$

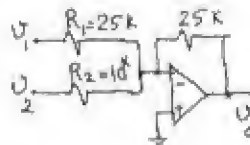
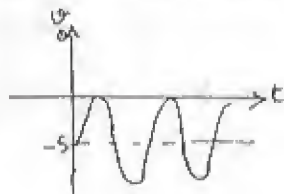
if we assume: $V_1 = 5 \sin \omega t$

$$V_2 = 2V \quad \left. \begin{array}{l} V_1 = 5 \sin \omega t \\ V_2 = 2V \end{array} \right\} V_o = -V_1 + 2.5V_2$$

In a weighted summer configuration:

$$\frac{R_F}{R_1} = +1 \quad \frac{R_F}{R_2} = 2.5$$

$$R_2 = 10k\Omega \Rightarrow R_F = 25k\Omega = R_1$$



we want to have: $V_o = 10V_1 - 10V_2$

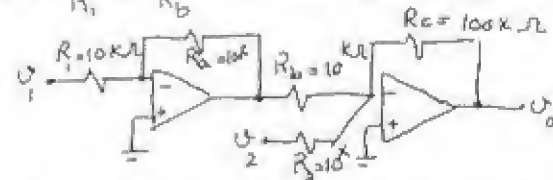
we use the circuit in Fig. 2.11.

According to Eq. 2.8:

$$V_o = V_1 \frac{R_a}{R_1} \frac{R_c}{R_b} - V_2 \frac{R_c}{R_3}$$

$$\frac{R_a}{R_1} \frac{R_c}{R_b} = 10, \quad \frac{R_c}{R_3} = 10, \quad \text{if } R_3 = 10k\Omega \Rightarrow R_c = 100k\Omega$$

$$\Rightarrow \frac{R_a}{R_1} \times \frac{100k\Omega}{R_b} = 10 \Rightarrow R_a = R_1 = R_b = 10k\Omega$$



$$V_o = 10V_1 - 10V_2 = 10 \times 0.02 \sin 2\pi \times 1000t - 10 \times 0.02 \sin(2\pi \times 1000t) = 0.2 \sin(2\pi \times 1000t) - 0.2 \sin(2\pi \times 1000t)$$

2.41

$$V_o = V_1 + 2V_2 - 3V_3 - 4V_4 \quad \text{Consider Fig. 2.11.}$$

According to eq. 2.8 for a weighted summer circuit:

$$V_o = V_1 \frac{R_a}{R_1} \frac{R_c}{R_b} + V_2 \frac{R_a}{R_2} \frac{R_c}{R_b} - V_3 \frac{R_c}{R_3} - V_4 \frac{R_c}{R_4}$$

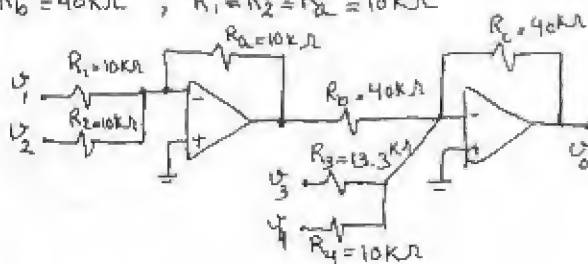
$$\frac{R_a}{R_1} \frac{R_c}{R_b} = 1, \quad \frac{R_a}{R_2} \frac{R_c}{R_b} = 1, \quad \frac{R_c}{R_3} = 3, \quad \frac{R_c}{R_4} = 4$$

assume:

$$R_4 = 10k\Omega \Rightarrow R_c = 40k\Omega \Rightarrow R_3 = \frac{40}{3} = 13.3k\Omega$$

$$\frac{R_a}{R_1} \times \frac{40}{R_b} = 1 \quad \frac{R_a}{R_2} \times \frac{40}{R_b} = 1$$

$$R_b = 40k\Omega, \quad R_1 = R_2 = R_a = 10k\Omega$$



2.43

This is a weighted summer circuit:

$$V_o = -\left(\frac{R_F}{R_1} V_1 + \frac{R_F}{R_2} V_2 + \frac{R_F}{R_3} V_3 + \frac{R_F}{R_4} V_4\right)$$

$$\text{we may write: } V_1 = 5V \times a_1, \quad V_2 = 5V \times a_2, \quad V_3 = 5V \times a_3, \quad V_4 = 5V \times a_4$$

$$V_o = -R_F \left(\frac{5a_1}{80k} + \frac{5a_2}{40k} + \frac{5a_3}{20k} + \frac{5a_4}{10k} \right)$$

$$V_o = -R_F \left(\frac{a_1}{16} + \frac{a_2}{8} + \frac{a_3}{4} + \frac{a_4}{2} \right)$$

$$V_o = -\frac{R_F}{16} (2a_1 + 2a_2 + 2a_3 + 2a_4)$$

$$-12 \leq V_o \leq 0 \Rightarrow \frac{R_F}{16} (2 \times 1 + 2 \times 1 + 2 \times 1 + 2 \times 1) =$$

$$= \frac{15 R_F}{16} = 12 \quad \text{when } a_1 = a_2 = a_3 = a_4 = 1 \text{ we have the peak value at } V_o.$$

$$\Rightarrow R_F = 12.8k\Omega$$

2.42

$$V_1 = 3 \sin(2\pi \times 60t) + 0.01 \sin(2\pi \times 1000t)$$

$$V_2 = 3 \sin(2\pi \times 60t) - 0.01 \sin(2\pi \times 1000t)$$

2.44

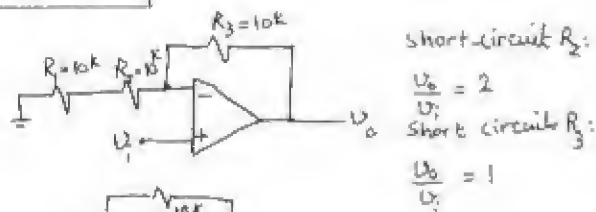
$$a) \frac{V_o}{V_1} = 1 = 1 + \frac{R_2}{R_1} \Rightarrow R_2 = 0, R_1 = 10k\Omega$$

$$b) \frac{V_o}{V_1} = 2 = 1 + \frac{R_2}{R_1} \Rightarrow R_2 = R_1 = 10k\Omega$$

Cont.

c) $\frac{U_o}{U_i} = 101 \text{ V/V} = 1 + \frac{R_2}{R_1} \Rightarrow \text{if } R_1 = 10 \text{ k}\Omega \Rightarrow R_2 = 1 \text{ M}\Omega$
d) $\frac{U_o}{U_i} = 100 \text{ V/V} = 1 + \frac{R_2}{R_1} \Rightarrow \text{if } R_1 = 10 \text{ k}\Omega \Rightarrow R_2 = 990 \text{ k}\Omega$

2.45



2.46

$U_+ = U_- = V = R \times i$, $i = 100 \mu\text{A}$ when $V = 10 \text{ V}$
 $\Rightarrow R = \frac{10}{0.1 \text{ mA}} = 100 \text{ k}\Omega$

As indicated, i only depends on R and V and the meter resistance does not affect i .

2.47

Refer to the circuit in P2.47:

a) using superposition, we first set $U_1 = U_2 = \dots = 0$
The output voltage that results in response to $U_{N1}, U_{N2}, \dots, U_{Nn}$ is:

$$U_{ON} = -\left(\frac{R_F}{R_{N1}} U_{N1} + \frac{R_F}{R_{N2}} U_{N2} + \dots + \frac{R_F}{R_{Nn}} U_{Nn}\right)$$

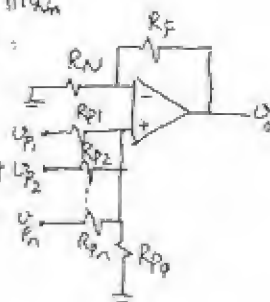
Then we set $U_{N1} = U_{N2} = \dots = 0$, then:

$$R_N = R_{N1} \parallel R_{N2} \parallel R_{N3} \parallel \dots \parallel R_{Nn}$$

The circuit simplifies to:

$$U_{Op} = \left(1 + \frac{R_F}{R_N}\right) \times$$

$$\left(\frac{U_{P1}}{\frac{1}{R_1} + \frac{1}{R_2} + \dots + \frac{1}{R_n}} + \frac{U_{P2}}{\frac{1}{R_1} + \frac{1}{R_2} + \dots + \frac{1}{R_n}} + \dots + \frac{U_{Pn}}{\frac{1}{R_1} + \frac{1}{R_2} + \dots + \frac{1}{R_n}}\right)$$



$$U_{Op} = \left(1 + \frac{R_F}{R_N}\right) \left(\frac{U_{P1}}{\frac{R_F}{R_1}} + \frac{U_{P2}}{\frac{R_F}{R_2}} + \dots + \frac{U_{Pn}}{\frac{R_F}{R_n}}\right)$$

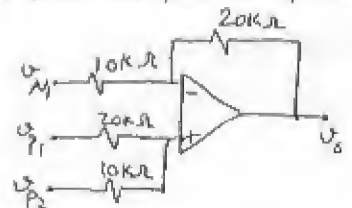
where:
 $R_p = R_{P1} \parallel R_{P2} \parallel \dots \parallel R_{Pn}$

when all inputs are present:

$$U_o = U_{ON} + U_{Op} = -\left(\frac{R_F}{R_{N1}} U_{N1} + \frac{R_F}{R_{N2}} U_{N2} + \dots\right) + \left(1 + \frac{R_F}{R_N}\right) \left(\frac{R_P}{R_1} U_{N1} + \frac{R_P}{R_2} U_{N2} + \dots\right)$$

b) $U_o = -2U_{N1} + U_{P1} + 2U_{P2}$
 $\frac{R_F}{R_{N1}} = 2$ if $R_{N1} = 10 \text{ k}\Omega \Rightarrow R_F = 20 \text{ k}\Omega$
 $\left(1 + \frac{R_F}{R_N}\right) \left(\frac{R_P}{R_1}\right) = 1 \Rightarrow 3 \frac{R_P}{R_1} = 1 \Rightarrow R_{P2} = \frac{R_{P1}}{2}$
 $\left(1 + \frac{R_F}{R_N}\right) \left(\frac{R_P}{R_2}\right) = 2 \Rightarrow 3 \frac{R_P}{R_2} = 2 \Rightarrow R_{P2} = \frac{R_{P1}}{2}$
where $R_p = \frac{R_{P1} \cdot R_{P2}}{R_{P1} + R_{P2}}$ (ignoring R_{Pn})

Note that if the results from the last 2 constraints differ, we would use an additional resistor connected from the positive input to ground. (R_{P0})



2.48

$$U_o = U_{I1} + 3U_{I2} - 2(U_{I3} + 3U_{I4})$$

Refer to P2.47.

$$\frac{R_F}{R_{N3}} = 2 \text{ if } R_{N3} = 10 \text{ k}\Omega \Rightarrow R_F = 20 \text{ k}\Omega$$

$$\frac{R_F}{R_{N4}} = 6 \Rightarrow R_{N4} = \frac{20}{6} = 3.3 \text{ k}\Omega$$

$$R_N = R_{N3} \parallel R_{N4} = 10 \text{ k}\Omega \parallel 3.3 \text{ k}\Omega = 2.48 \text{ k}\Omega$$

$$\left(1 + \frac{R_F}{R_N}\right) \frac{R_P}{R_2} = 1 \Rightarrow \left(1 + \frac{20}{2.48}\right) \frac{R_P}{R_2} = 1 \Rightarrow 9.06 R_P = R_2$$

$$R_p = R_{P1} \parallel R_{P2} \parallel R_{P0} \Rightarrow R_p = \frac{1}{\frac{1}{R_{P1}} + \frac{1}{R_{P2}} + \frac{1}{R_{P0}}}$$

$$\left(1 + \frac{R_F}{R_N}\right) \frac{R_P}{R_2} = 3 \Rightarrow 9.06 \frac{R_P}{R_2} = 3 \Rightarrow R_2 \approx 3 R_P$$

$$R_{P1} \parallel R_{P2} = \frac{9 \times 3 R_P}{9 + 3} = 2.25 R_P, R_p = 2.25 R_P \parallel R_{P0}$$

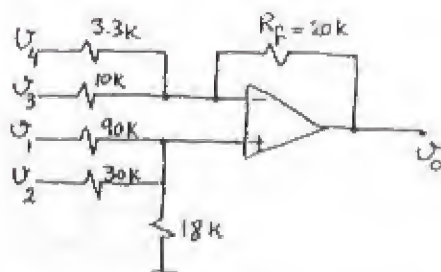
Cont.

$$2.25 R_p + R_{p0} = 2.25 R_{p0} \Rightarrow R_{p0} = 1.8 R_p$$

$$\text{if } R_p = 10 \text{ k}\Omega \Rightarrow R_{p0} = 18 \text{ k}\Omega$$

$$R_{p1} = 9 \times 10 \text{ k} = 90 \text{ k}\Omega$$

$$R_{p2} = 3 \times 10 \text{ k} = 30 \text{ k}\Omega$$



2.49

$$U_+ = U_- = \frac{R_4}{R_3 + R_4} U$$

$$\frac{U_o}{R_1} = \frac{U_- - U_-}{R_2} \Rightarrow U_o = U_- \left(1 + \frac{R_2}{R_1}\right)$$

from the two above equations:

$$\frac{U_o}{U_1} = \left(1 + \frac{R_2}{R_1}\right) \left(\frac{R_4}{R_3 + R_4}\right) = \frac{1 + R_2/R_1}{1 + R_3/R_4}$$

2.50

Refer to Fig. 2.50. Setting $U_2 = 0$, we obtain the output component due to U_1 as:

$$U_{o1} = -20V$$

Setting $U_1 = 0$, we obtain the output component due to U_2 as:

$$U_{o2} = U_2 \left(1 + \frac{20R}{R}\right) \left(\frac{20R}{20R + R}\right) = 20U_2$$

The total output voltage is:

$$U_o = U_{o1} + U_{o2} = 20(U_2 - U_1)$$

$$\text{For } U_1 = 10 \sin 2\pi \times 60t - 0.1 \sin(2\pi \times 1000t)$$

$$U_2 = 10 \sin 2\pi \times 60t + 0.1 \sin(2\pi \times 1000t)$$

$$U_o = 4 \sin(2\pi \times 1000t)$$

2.51

$$\frac{U_o}{U_1} = 1 + \frac{R_2}{R_1} = 1 + \frac{(1-x)}{x} = 1 + \frac{1}{x} - 1 = \frac{1}{x}$$

$$0 < x < 1 \Rightarrow 1 \leq \frac{U_o}{U_1} < \infty$$

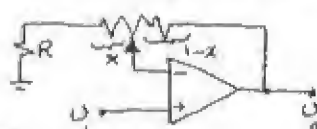
if we add a resistor on the ground path:

$$\frac{U_o}{U_1} = 1 + \frac{(1-x) \times 10K}{x \times 10K + R}$$

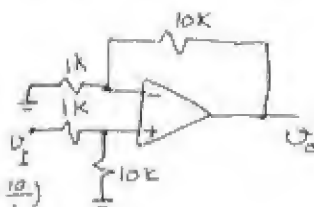
$$\text{Gain}_{\max} = 21 \text{ when}$$

$$x=0 \Rightarrow 21 = 1 + \frac{10K}{R}$$

$$\Rightarrow R = \frac{10K}{20} = 0.5 \text{ k}\Omega$$



2.52



$$U_o = U_1 \frac{10}{1+10} \left(1 + \frac{10}{1}\right)$$

$$U_o = 10U_1$$

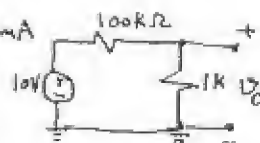
2.53

a) Source is connected directly.

$$U_o = 10 \times \frac{1}{101} = 0.099V$$

$$i_L = \frac{U_o}{1K} = \frac{0.099}{1K} = 0.099 \text{ mA}$$

current supplied by the source is 0.099 mA.



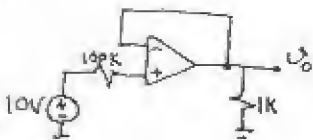
b) inserting a buffer

$$U_o = 10V$$

$$i_L = \frac{10V}{1K} = 10 \text{ mA}$$

current supplied by the 10V source is 0.

The load current i_L comes from the power supply of the op-amp.



2.54

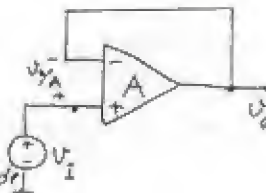
$$V_o = V_i - \frac{V_o}{A}$$

$$\frac{V_o}{V_i} = \frac{1}{1 + \frac{1}{A}}$$

error of Gain magnitude

$$\left| \frac{V_o}{V_i} - 1 \right| = -\frac{1}{A+1}$$

A (V/V)	1000	100	10
$\frac{V_o}{V_i}$ (V/V)	0.999	0.990	0.909
Gain Error	-0.1%	-1%	-9.1%



2.55

for an inverting amplifier:

$$R_i = R_1, \quad G = -\frac{R_2}{R_1}$$

for a non-inverting amplifier:

$$R_i = \infty, \quad G = 1 + \frac{R_2}{R_1}$$

Case	Gain	R_{in}	R_1	R_2
a	-10	10K	10K	100K
b	-1	100K	100K	100K
c	-2	50K	50K	100K
d	+1	∞	10K	10K
e	+2	∞	10K	10K
f	+11	∞	10K	100K
g	-0.5	10K	10K	5K

2.56

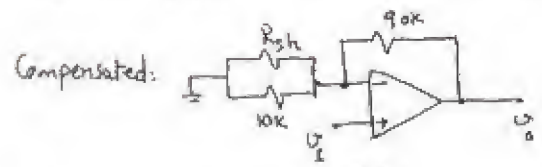
$$A = 50 \text{ V/V}, \quad 1 + \frac{R_2}{R_1} = 10 \text{ V/V}$$

$$\text{if } R_1 = 10 \text{ K}\Omega \Rightarrow R_2 = 90 \text{ K}\Omega$$

According to Eq. 2.11: $G = \frac{V_o}{V_i} = \frac{1 + \frac{R_2}{R_1}}{1 + \frac{1}{A}}$

$$G = \frac{1 + \frac{90}{10}}{1 + \frac{1}{50}} = \frac{10}{1.2} = 8.33 \text{ V/V}$$

In order to compensate the gain drop,

we can shunt a resistor with R_1 .

Compensated:

$$R_{sh}: 10 = \frac{1 + \frac{90}{10} + \frac{90}{R_{sh}}}{1 + \frac{1}{1 + \frac{90}{10} + \frac{90}{R_{sh}}}} \Rightarrow$$

$$10 \times (50R_{sh} + 90R_{sh} + 900) = 50(10R_{sh} + 90R_{sh} + 900)$$

$$100R_{sh} = 3600 \Rightarrow R_{sh} = 36 \text{ K}\Omega$$

if $A = 100$ then:

$$G_{\text{uncompensated}} = \frac{1 + \frac{90}{10}}{1 + \frac{1}{100}} = \frac{10}{1.1} = 9.09 \text{ V/V}$$

$$G_{\text{compensated}} = \frac{1 + \frac{90}{10} + \frac{90}{36}}{1 + \frac{1}{100}} = \frac{12.5}{1.125} = 11.1 \text{ V/V}$$

2.57

$$G = \frac{G_o}{1 + \frac{G_o}{A}}, \quad \frac{G_o - G}{G_o} \times 100 = \frac{G_o/A \times 100}{1 + \frac{G_o}{A}} \%$$

$$\text{or } \frac{1 + \frac{G_o}{A}}{\frac{G_o}{A}} \geq \frac{100}{x} \Rightarrow \frac{A}{G_o} \geq \left(\frac{100}{x} - 1 \right)$$

$$\Rightarrow A \geq G_o F \text{ where } F = \frac{100}{x} - 1 \leq \frac{100}{x}$$

x	0.01	0.1	1	10
F	10^4	10^3	10^2	10

Thus for:

$$x = 0.01: \begin{array}{ccccc} G_o (V/V) & 1 & 10 & 10^2 & 10^3 & 10^4 \\ A (V/V) & 10^4 & 10^5 & 10^6 & 10^7 & 10^8 \end{array}$$

too high to be practical

$$x = 0.1: \begin{array}{ccccc} G_o (V/V) & 1 & 10 & 10^2 & 10^3 & 10^4 \\ A (V/V) & 10^3 & 10^4 & 10^5 & 10^6 & 10^7 \end{array}$$

$$x = 1: \begin{array}{ccccc} G_o (V/V) & 1 & 10 & 10^2 & 10^3 & 10^4 \\ A (V/V) & 10^2 & 10^3 & 10^4 & 10^5 & 10^6 \end{array}$$

$$x = 10: \begin{array}{ccccc} G_o (V/V) & 1 & 10 & 10^2 & 10^3 & 10^4 \\ A (V/V) & 10 & 10^2 & 10^3 & 10^4 & 10^5 \end{array}$$

2.58

for non-inverting amplifier, Eq. 2.11:

$$G = \frac{G_o}{1 + \frac{G_o}{A}}, \quad E = \frac{G_o - G}{G_o} \times 100$$

for inverting amplifier, Eq. 2.5:

$$G = \frac{G_o}{1 + \frac{1 - G_o}{A}}, \quad E = \frac{G_o - G}{G_o} \times 100$$

Case	$G_o (V/V)$	$A (V/V)$	$G (V/V)$	$E \%$
a	-1	10	-0.83	16
b	1	10	0.91	9
c	-1	100	-0.98	2
d	10	10	5	50
e	-10	100	-9	10
f	-10	1000	-9.89	1.1
g	+1	2	0.67	33

2.59

Refer to Fig. P2.59, when potentiometer is set to the bottom:

$$V_o = V_+ = -15 + \frac{30 \times 20}{20 + 100 + 20} = -10.714 \text{ V}$$

$$\text{when set to the top: } V_o = -15 + \frac{30 \times 120}{20 + 100 + 20} = 10.714 \text{ V}$$

$$\Rightarrow -10.714 \leq V_o \leq 10.714$$

$$\text{pot has 20 turn, each turn, } \Delta V_o = \frac{2 \times 10.714}{20} = 1.07 \text{ V}$$

2.60

Refer to Fig. 2.16. Notice that similar to eq. 2.15 we have: $\frac{R_4}{R_3} = \frac{R_2}{R_1} = \frac{100}{10}$. therefore according to 2.16:

$$V_o = \frac{R_2}{R_1} V_{id} \Rightarrow A = \frac{R_2}{R_1} = 10 \text{ V/V}$$

According to 2.20: $R_{id} = 2R_1 = 20 \text{ k}\Omega$ If $\frac{R_2}{R_1}$, $\frac{R_4}{R_3}$ were different by $i\%$:

$$\frac{R_2}{R_1} = 0.99 \frac{R_4}{R_3}$$

$$\text{Refer to eq. 2.19: } A_{cm} = \frac{R_4}{R_4 + R_3} \left(1 - \frac{R_2}{R_1} \frac{R_3}{R_4} \right)$$

$$A_{cm} = \frac{100}{100 + 10} (1 - 0.99) = 0.009$$

$$\text{CMRR} = 20 \log \frac{|A_d|}{|A_{cm}|}, \text{ so let's calculate } A_d$$

$$A_d = \frac{V_o}{V_{id}} \text{ if we apply superposition:}$$

$$V_{o1} = -\frac{R_2}{R_1} V_{I1} \quad V_{o2} = V_{I2} \frac{R_4}{R_3 + R_4} \left(1 + \frac{R_2}{R_1} \right)$$

$$V_o = V_{o2} + V_{o1} = V_{I2} \frac{R_4/R_3}{1 + \frac{R_4}{R_3}} \left(1 + \frac{R_2}{R_1} \right) - \frac{R_2}{R_1} V_{I1}$$

$$\text{Replace } \frac{R_2}{R_1} = 0.99 \frac{R_4}{R_3} \Rightarrow \frac{R_2}{R_1} = 0.99 \times \frac{100}{10} = 9.9$$

$$V_o = V_{I2} \frac{10}{1 + 10} (1 + 9.9) - V_{I1} 9.9 = 9.9 (V_{I2} - V_{I1})$$

$$\frac{V_o}{V_{id}} = 9.9 = A_d \Rightarrow \text{CMRR} = 20 \log \frac{9.9}{0.009} = 60.8$$

$$\text{CMRR} = 60.8$$

2.61

If we assume $R_3 = R_1$, $R_4 = R_2$, then

$$\text{eq. 2.20: } R_{id} = 2R_1 \Rightarrow R_1 = \frac{20}{2} = 10 \text{ k}\Omega$$

(Refer to Fig. 2.16)

$$\text{a) } A_d = \frac{R_2}{R_1} = 1 \text{ V/V} \Rightarrow R_2 = 10 \text{ k}\Omega$$

$$R_1 = R_2 = R_3 = R_4 = 10 \text{ k}\Omega$$

$$\text{b) } A_d = \frac{R_2}{R_1} = 2 \text{ V/V} \Rightarrow R_2 = 20 \text{ k}\Omega = R_4$$

$$R_1 = R_3 = 10 \text{ k}\Omega$$

$$\text{c) } A_d = \frac{R_2}{R_1} = 100 \text{ V/V} \Rightarrow R_2 = 1 \text{ M}\Omega = R_4$$

$$R_1 = R_3 = 10 \text{ k}\Omega$$

$$\text{d) } A_d = \frac{R_2}{R_1} = 0.5 \text{ V/V} \Rightarrow R_2 = 5 \text{ k}\Omega = R_4$$

$$R_1 = R_3 = 10 \text{ k}\Omega$$

2.62

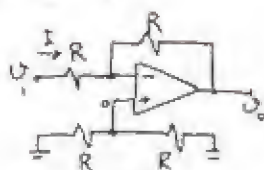
Refer to Fig P2.62:

Cont.

Considering that $V_- = V_+$:

$$V_1 + \frac{V_0 - V_1}{2} = \frac{V_2}{2} \Rightarrow V_0 = V_2 - V_1$$

$$V_1 \text{ only: } R_1 = \frac{V_1}{I} = R$$



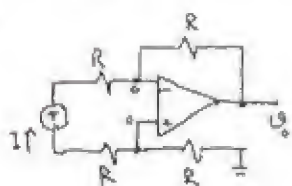
$$V_2 \text{ only: } R_1 = \frac{V_2}{I} = 2R$$



V_3 between 2 terminals:

$$R_1 = \frac{V}{I} = 2R$$

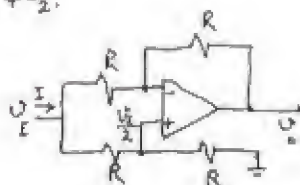
$$V_+ = V_- = 0$$



V_3 connected to both V_1 & V_2 :

$$R_1 = \frac{V}{I} = R$$

$$V_+ = V_- = \frac{V}{2}$$



2.63

$$V_+ = V_{CM} \frac{R_4}{R_3 + R_4}$$

$$V_+ = V_-$$

$$i_2 = \frac{V_{CM}}{R_3 + R_4}$$

$$i_1 = \frac{V_{CM}}{R_1} - \frac{V_{CM} R_4}{R_3 + R_4} \cdot \frac{1}{R_1} = \frac{V_{CM}}{R_1} \frac{R_3}{R_3 + R_4}$$

$$i = i_1 + i_2 = \frac{V_{CM}}{R_1} \frac{R_3}{R_3 + R_4} + \frac{V_{CM}}{R_3 + R_4}$$

$$\frac{1}{R_I} = \frac{i}{V_{CM}} = \frac{1}{R_1} \frac{1}{\frac{R_4}{R_3} + 1} + \frac{1}{R_3 + R_4}$$

if we replace $\frac{R_4}{R_3}$ with $\frac{R_2}{R_1}$: ($\frac{R_4}{R_3} = \frac{R_2}{R_1}$)

$$\frac{1}{R_I} = \frac{1}{R_1 + R_2} + \frac{1}{R_3 + R_4} \Rightarrow R_I = (R_1 + R_2) \parallel (R_3 + R_4)$$

2.64

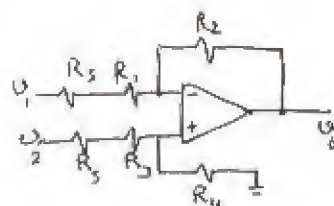
In order to have an ideal differential amp:

$$\frac{R_3 + R_1}{R_2} = \frac{R_5 + R_3}{R_4}$$

$$\frac{R_3/R_1 + 1}{R_2/R_1} = \frac{R_3/R_3 + 1}{R_4/R_3}$$

$$\text{Since } \frac{R_2}{R_1} = \frac{R_4}{R_3}:$$

$$\frac{R_5}{R_1} + 1 = \frac{R_3}{R_3} + 1 \Rightarrow R_1 = R_3 \Rightarrow R_2 = R_4$$



2.65

Refer to eq. 2.19 and Fig. P2.62:

$$A_{cm} = \frac{V_0}{V_{CM}} = \frac{R_4}{R_3 + R_4} \left(1 - \frac{R_2}{R_1} \frac{R_3}{R_4} \right)$$

The worst case is when A_{cm} has its maximum value.

$$A_{cm} = \frac{1}{\frac{R_3}{R_4} + 1} \left(1 - \frac{R_2}{R_1} \frac{R_3}{R_4} \right)$$

Max $A_{cm} = r \frac{R_2}{R_4}$ has to be at its minimum value and also $R_4 \frac{R_2}{R_1}$ has to be minimum.

$$\frac{100-x}{100+x} \frac{R_3}{R_4} \leq \frac{100+x}{100-x} \frac{R_2}{R_1} \leq \frac{100+x}{100-x}$$

$$\text{so if } \frac{R_3}{R_4} = \frac{100-x}{100+x} \text{ \& } \frac{R_2}{R_1} = \frac{100-x}{100+x}$$

$$A_{cm \text{ Max}} = \frac{1}{\frac{100-x}{100+x} + 1} \left(1 - \frac{100-x}{100+x} \frac{100-x}{100+x} \right)$$

$$A_{cm \text{ Max}} = \frac{1}{200} \frac{(100+x)^2 - (100-x)^2}{100+x} = \frac{2x}{100+x} \cdot \frac{1}{50}$$

x	0.1	1	5
$A_{cm \text{ Max}}$	0.002	0.02	0.1

$CHRR = 20 \log |A_d|$. Now we have to calculate

A_d based on values we chose for $R_1 - R_4$

that gave us $A_{cm \text{ Max}}$.

$$R_2 = R_3 = 100 - x \quad R_1 = R_4 = 100 + x$$

$V_0 = V_{01} + V_{02}$ by applying superposition

$$V_0 = \frac{R_2}{R_1} V_1 + V_2 \frac{R_4}{R_3 + R_4} \left(1 + \frac{R_2}{R_1} \right)$$

$$V_0 = -\frac{100-x}{100+x} V_1 + V_2 \frac{100+x}{200} \left(1 + \frac{100-x}{100+x} \right)$$

$$V_0 = -\frac{100-x}{100+x} V_1 + V_2$$

$$\text{if we consider } \frac{100-x}{100+x} \leq 1 \Rightarrow \frac{V_0}{V_{id}} \approx 1 \quad \text{Cont.}$$

$$CMRR = 20 \log \frac{A_d}{A_{cm}} = 20 \log \frac{1}{1/50} = 20 \log 50$$

x	0.1	1	5
CMRR	54db	34db	20db

2.66

Refer to Fig. 2.16 and Eq. 2.19:

$$A_{cm} = \frac{R_u}{R_3 + R_4} \left(1 - \frac{R_2}{R_1} \frac{R_3}{R_4} \right)$$

In order to calculate A_d , we use superposition principle:

$$V_o = V_{o1} + V_{o2} = -\frac{R_2}{R_1} V_1 + V_2 \frac{R_4}{R_3 + R_4} \left(1 + \frac{R_2}{R_1} \right)$$

then replace $V_1 = V_{cm} - \frac{V_d}{2}$

$$V_2 = V_{cm} + \frac{V_d}{2}$$

$$V_o = -\frac{R_2}{R_1} V_{cm} + \frac{R_2}{R_1} V_d/2 + V_{cm} \frac{1 + R_2/R_1}{1 + R_3/R_4} + \frac{V_d/2}{2} \frac{1 + R_2/R_1}{1 + R_3/R_4}$$

$$V_o = \frac{R_2}{2R_1} \left[1 + \frac{R_1/R_4 + 1}{R_3/R_4 + 1} \right] V_d + \frac{R_2}{R_1} \left[1 + \frac{R_1/R_4 + 1}{R_3/R_4 + 1} \right] V_{cm}$$

$$CMRR = 20 \log \left| \frac{A_d}{A_{cm}} \right| = 20 \log \left| \frac{\frac{R_2}{2R_1} \left[1 + \frac{R_1/R_4 + 1}{R_3/R_4 + 1} \right]}{\frac{R_2}{R_1} \left[1 + \frac{R_1/R_4 + 1}{R_3/R_4 + 1} \right]} \right|$$

$$CMRR = 20 \log \left| \frac{\frac{1}{2} \frac{R_2}{R_1} \left[2 + \frac{R_1}{R_3} + \frac{R_3}{R_4} \right]}{1 - \frac{R_2}{R_1} \frac{R_3}{R_4}} \right|$$

$$CMRR = 20 \log \left| \frac{1 + \frac{1}{2} \frac{R_1}{R_2} + \frac{1}{2} \frac{R_3}{R_4}}{\frac{R_1}{R_2} - \frac{R_3}{R_4}} \right|$$

For worst case, or minimum CMRR we have to maximize the denominator, which means:

$$R_1 = R_{1n} (1 + \epsilon) \quad R_3 = R_{3n} (1 - \epsilon)$$

$$R_2 = R_{2n} (1 - \epsilon) \quad R_4 = R_{4n} (1 + \epsilon)$$

$$\text{also: } \frac{R_{2n}}{R_{1n}} = \frac{R_{4n}}{R_{3n}} = K$$

$$CMRR = 20 \log \left| K \frac{1 + \frac{1}{2K} \frac{1+\epsilon}{1-\epsilon} + \frac{1}{2K} \frac{1-\epsilon}{1+\epsilon}}{\frac{1+\epsilon}{1-\epsilon} - \frac{1-\epsilon}{1+\epsilon}} \right|$$

$$CMRR = 20 \log \left| \frac{K (1 - \epsilon^2) + (1 + \epsilon^2)}{4\epsilon} \right| = 20 \log \left| \frac{K+1}{4\epsilon} \right|$$

for $\epsilon^2 \ll 1$.

$$\text{if } K = A_{d \text{ ideal}} = 100, \epsilon = 0.01$$

$$CMRR = 20 \log \frac{101}{0.04} = 68 \text{ db}$$

2.67

$$A_d = 100$$

we assume $\frac{R_2}{R_1} = \frac{R_4}{R_3}$ then $A_d = \frac{R_2}{R_1} = K$
 $K \leq 100$

$$R_{id} = 2R_1 = 20 \text{ k}\Omega \Rightarrow R_1 = 10 \text{ k}\Omega$$

$$CMRR = 80 \text{ db} = 20 \log \frac{A_d}{A_{cm}} \Rightarrow \frac{A_d}{A_{cm}} = 10^4$$

$$\Rightarrow A_{cm} = 0.01$$

$$A_d = 100 = \frac{R_2}{R_1} \Rightarrow R_2 = 1 \text{ M}\Omega$$

$$\text{Refer to p 2.65: } CMRR = 20 \log \frac{K+1}{4\epsilon}$$

$$CMRR = 10^4$$

$$\Rightarrow \epsilon = 10^{-2} \times 0.25$$

We assumed earlier $\frac{R_2}{R_1} = \frac{R_4}{R_3}$ then

$$\frac{R_4}{R_3} \leq 100 \Rightarrow \text{if } R_3 = 10 \text{ k}\Omega \pm \epsilon$$

$$\Rightarrow R_4 = 1 \text{ M}\Omega \pm \epsilon$$

$$R_2 = 1 \text{ M}\Omega \pm \epsilon$$

$$R_1 = 10 \text{ k}\Omega \pm \epsilon$$

$$\epsilon = 0.25\%$$

2.68

Refer to Fig. P2.68 and Eq. 2.19:

$$A_{cm} = \frac{R_u}{R_3 + R_4} \left(1 - \frac{R_2}{R_1} \frac{R_3}{R_4} \right) = \frac{100}{100+100} \left(1 - \frac{100 \cdot 100}{100 \cdot 100} \right)$$

$$A_{cm} = 0$$

$$\text{Refer to 2.14: } \frac{R_2}{R_1} = \frac{R_4}{R_3}$$

$$\Rightarrow A_d = \frac{R_2}{R_1} = 1$$

b) Since $A_{cm} = 0$,

then if we apply V_{cm} to V_{i1} and V_{i2} :

V_{cm} to V_{i1} and V_{i2} :

$$V_o = 0$$

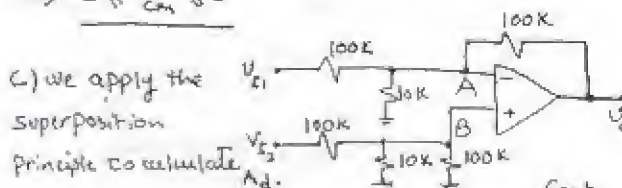
$$\text{Therefore, } V_A = V_{cm} \frac{100}{100+100}$$

$$V_A = \frac{V_{cm}}{2}$$

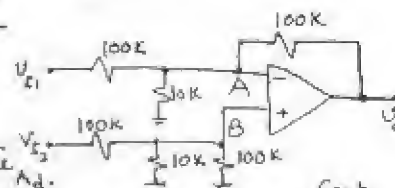
$$\text{Similarly, } V_B = \frac{V_{cm}}{2}$$

$$\text{We know } V_A = V_B \text{ and } -2.5 \leq V_A \leq 2.5$$

$$\Rightarrow -5 \leq V_{cm} \leq 5$$



c) we apply the superposition principle to calculate A_d .



Cont.

v_{o1} is the output voltage when $v_{i2}=0$

v_{o2} is the output voltage when $v_{i1}=0$

$$v_o = v_{o1} + v_{o2}$$

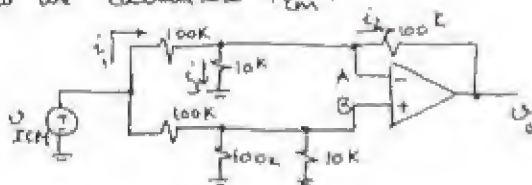
$$v_{o1} = -\frac{R_2}{R_1} v_{i1} = -v_{i1}$$

$$v_{o2} = v_{i2} \frac{100k \parallel 10k}{100k \parallel 10k + 100} \left(1 + \frac{100k}{100k \parallel 10k}\right)$$

$$v_{o2} = v_{i2}$$

$$\Rightarrow v_o = v_{o1} + v_{o2} = -v_{i1} + v_{i2} \Rightarrow A_d = 1$$

Now we calculate A_{cm} :



$$v_B = v_{ICM} \frac{100k \parallel 10k}{100k \parallel 10k + 100k}, \quad v_A = v_B$$

$$i_1 = \frac{v_{ICM} - v_A}{100k}$$

$$v_o = v_A - 100k i_2 \quad \text{and} \quad i_2 = i_1 - i_3 = i_1 - \frac{v_A}{10k}$$

$$v_o = v_A - 100k i_1 + 10 v_A$$

$$v_o = v_A - v_{ICM} + v_A + 10 v_A$$

$$v_A = v_B \Rightarrow v_o = v_{ICM} (-1 + 12 \frac{100k \parallel 10k}{100k \parallel 10k + 100k})$$

$$\frac{v_o}{v_{ICM}} = A_{cm} = 0$$

Now we calculate v_{ICM} range:

$$-25 \leq v_B \leq 2.5 \Rightarrow -2.5 v_{ICM} \times \frac{100k \parallel 10k}{100k \parallel 10k + 100k} < 2.5$$

$$-30 \leq v_{ICM} \leq 30V$$

2.69

Refer to Fig. P2.69; we use superposition:

$$v_o = v_{o1} + v_{o2}$$

$$\text{calculate } v_{o1}: v_+ = \frac{\beta v_{o1}}{2} = v_-$$

$$\frac{v_+}{2} = \frac{\beta v_{o1}}{2} - v_o \Rightarrow v_{o1} = \frac{v_+}{\beta - 1}$$

calculate v_{o2} :

$$v_- = \frac{v_{o2}}{2} = v_+ \Rightarrow v_- - \frac{v_{o2}}{2} = \frac{v_{o2}}{2} - \beta v_{o2}$$

$$\Rightarrow v_{o2} = \frac{v_+}{1 - \beta}$$

$$v_o = v_{o1} + v_{o2} = \frac{v_+}{\beta - 1} + \frac{v_+}{1 - \beta} = \frac{1}{1 - \beta} (v_- - v_+)$$

$$A_d = \frac{v_o}{v_- - v_+} = \frac{1}{1 - \beta}$$

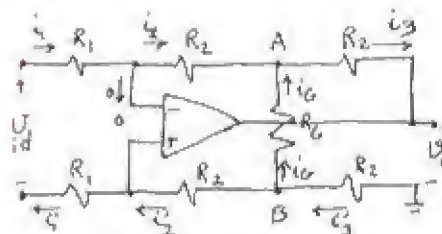
$$A_d = 10 \frac{V}{V} \Rightarrow \beta = 0.9 = \frac{R_5}{R_5 + R_6}$$

$$R_{id} = 2R = 2M\Omega \Rightarrow R = 1M\Omega$$

$$R_5 + R_6 \leq \frac{R}{100} \Rightarrow R_5 + R_6 \leq 10k\Omega$$

$$R_5 = 6.8k\Omega, R_6 = 680\Omega \Rightarrow \beta = \frac{6.8}{6.8 + 0.68} = 0.9$$

2.70



$v_+ = v_-$ so we can consider v_+, v_- a virtual

$$\text{short: } i_1 = \frac{v_{id}}{2R_1} \Rightarrow i_2 = \frac{v_{id}}{2R_1}$$

$$i_1' = i_2' = \frac{v_{id}}{2R_1}$$

$$\text{then: } i_2 R_2 + v_{AB} + i_2 R_2 = 0 \Rightarrow v_{AB} = -\frac{v_{id}}{R_1} R_2$$

$$i_G = \frac{v_{id}}{R_6} \times \frac{R_2}{R_1}$$

$$i_3 = i_2 + i_G = \frac{v_{id}}{2R_1} + \frac{v_{id}}{R_6} \frac{R_2}{R_1}$$

$$i_3 + i_G + i_2 = i_3$$

$$\Rightarrow v_o = -[i_3 R_2 + v_{AB} + i_3 R_2]$$

$$v_o = -[2i_3 R_2 + v_{AB}]$$

$$v_o = -\left[2 \frac{v_{id}}{2R_1} R_2 + 2 \frac{v_{id}}{R_6} \frac{R_2}{R_1} \frac{R_2}{R_6} + \frac{v_{id}}{R_1} R_2\right]$$

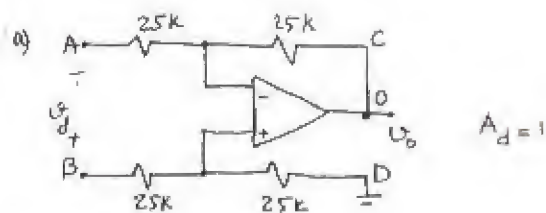
$$\frac{v_o}{v_{id}} = A_d = -2 \frac{R_2}{R_1} \left[1 + \frac{R_2}{R_6}\right]$$

2.71

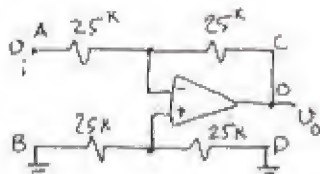
a)

Refer to Eq. 2.17: $A_d = \frac{R_2}{R_1} = 1$. Connect C and D together.

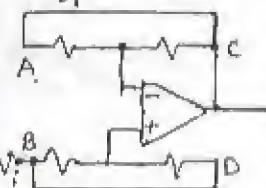
Cont.



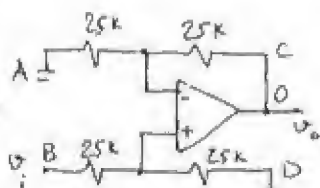
b) $\frac{v_o}{v_i} = -1 \frac{V}{V}$
 i)



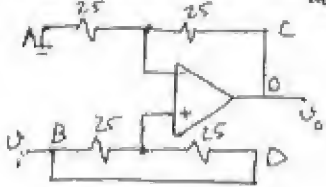
ii) $\frac{v_o}{v_i} = +1 \frac{V}{V}$



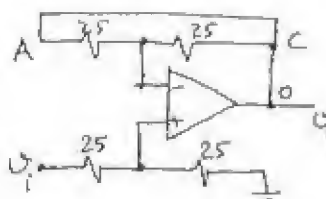
The circuit on the left ideally has infinite input resistance



iii) $\frac{v_o}{v_i} = +2 \frac{V}{V}$



iv) $\frac{v_o}{v_i} = +\frac{1}{2} \frac{V}{V}$



$v_o = \frac{v_i}{2} = \frac{v_o}{2}$
 $\Rightarrow \frac{v_o}{v_i} = \frac{1}{2}$

2.73

Refer to Fig. 2.20.a.

The gain of the first stage is: $(1 + \frac{R_2}{R_1}) = 101$

If the opamps of the first stage saturate at

$54V$ $\Rightarrow -14 \leq v_i \leq +14V \Rightarrow -14 \leq 101 v_{icm} \leq +14$
 $\Rightarrow -0.14 \leq v_{icm} \leq 0.14$

As explained in the text, the disadvantage of circuit in Fig. 2.20.a is that v_{icm} is amplified by a gain equal to $v_{id} (1 + \frac{R_2}{R_1})$ in the first stage and therefore a very small v_{icm} range is acceptable to avoid saturation.

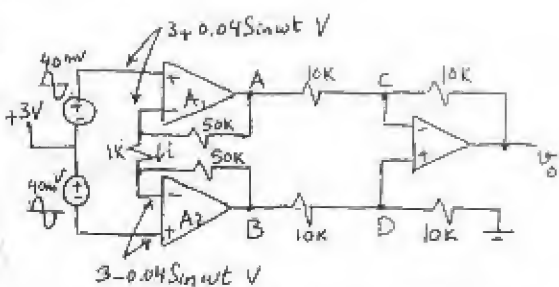
b) In Fig. 2.20.b, when v_{icm} is applied, v_i for both A_1 & A_2 is the same and therefore no current flows through $2R_1$. This means voltage at the output of A_1 and A_2 is the same as v_{icm} .

$-14 \leq v_o \leq +14 \Rightarrow -14 \leq v_{icm} \leq +14$

This circuit allows for bigger range of v_{icm} .

2.74

2.72



$i = \frac{3 + 0.04 \sin \omega t - (3 - 0.04 \sin \omega t)}{1k} = 0.08 \sin \omega t, \mu A$

$v_A = 3 + 0.04 \sin \omega t + 50k \times i = 3 + 4.04 \sin \omega t, V$

$v_B = 3 - 0.04 \sin \omega t - 50k \times i = 3 - 4.04 \sin \omega t, V$

$v_C = v_D = \frac{1}{2} v_B = 1.5 - 2.02 \sin \omega t, V$

$v_o = v_B - v_A = -8.08 \sin \omega t, V$

$v_{i1} = v_{cm} - v_d/2$

$v_{i2} = v_{cm} + v_d/2$

Refer to Fig. 2.20.a.

output of the first stage is: $(1 + \frac{R_2}{R_1})(v_{cm} - v_d/2)$

$v_{o1} = (1 + \frac{R_2}{R_1})(v_{cm} - v_d/2)$

$v_{o2} = (1 + \frac{R_2}{R_1})(v_{cm} + v_d/2)$

$v_{o2} - v_{o1} = (1 + \frac{R_2}{R_1}) v_d \Rightarrow A_{d(1)} = 1 + \frac{R_2}{R_1}$

$\frac{v_{o2} + v_{o1}}{2} = (1 + \frac{R_2}{R_1}) v_{cm} \Rightarrow A_{cm(1)} = 1 + \frac{R_2}{R_1}$

$CMRR = 20 \log \left| \frac{A_d}{A_{cm}} \right| = 0$ (First stage)

Now Consider Fig. 2.20.b

$v_{o1} = v_{i1} + \frac{R_2}{2R_1} (v_{i1} - v_{i2})$

$v_{o1} = v_{cm} - v_d/2 + \frac{R_2}{2R_1} (-v_d)$

Cont.

$$v_{o1} = v_{cm} - \frac{v_d}{2} \left(1 + \frac{R_2}{R_1}\right)$$

$$v_{o2} = v_{i2} - R_2 \cdot \frac{v_{i1} - v_{i2}}{2R_1} = v_{cm} + \frac{v_d}{2} + R_2 \cdot \frac{v_d}{2R_1}$$

$$v_{o2} = v_{cm} + \frac{v_d}{2} \left(1 + \frac{R_2}{R_1}\right)$$

$$v_{o2} - v_{o1} = v_d \left(1 + \frac{R_2}{R_1}\right) \Rightarrow A_{d(1)} = 1 + \frac{R_2}{R_1}$$

$$\frac{v_{o2} + v_{o1}}{2} = v_{cm} \Rightarrow A_{cm(1)} = 1$$

$$CMRR = 20 \log \left| \frac{A_d}{A_{cm}} \right| = 20 \log \left(1 + \frac{R_2}{R_1}\right)$$

In 2.20.b, the common mode voltage is not amplified and it is only propagated to the outputs of the first stage.

2.75

Refer to eq. 2.22:

$$A_d = \frac{R_4}{R_3} \left(1 + \frac{R_2}{R_1}\right) = \frac{100k}{100k} \left(1 + \frac{100k}{5k}\right) = 21 \frac{V}{V}$$

$$A_{cm} = 0$$

$$CMRR = 20 \log \left| \frac{A_d}{A_{cm}} \right| = \infty$$

If all resistors are $\pm 1\%$:

$$A_d \approx 21$$

In order to calculate A_{cm} , apply v_{cm} to both inputs and note that v_{cm} will appear at both output terminals of the first stage.

Now we can evaluate v_o by analyzing the second stage as was done in problem 2.65.

In P2.65 we showed that if each $100k$ resistor has $\pm x\%$ tolerance, A_{cm} of the differential amplifier is: $A_{cm} = \frac{v_o}{v_{cm}} = \frac{x}{50}$. Therefore the overall A_{cm} is also $\frac{x}{50}$.

$$x = 1 \Rightarrow A_{cm} = \frac{1}{50} = 0.02$$

$$CMRR = 20 \log \frac{21}{0.02} = 60 \text{ dB}$$

$$\text{If } 2R_1 = 1k\Omega : A_d = \frac{R_4}{R_3} \left(1 + \frac{R_2}{R_1}\right) = 201 \frac{V}{V}$$

$$A_{cm} = 0.02 \text{ unchanged}$$

$$CMRR = 20 \log \frac{201}{0.02} = 80 \text{ dB}$$

Conclusion: Large CMRR can be achieved by

having relatively large A_d in the first stage.

2.76

A_d of the second stage is $\frac{R_4}{R_3} = 0.5$

$$R_4 = 100k\Omega, R_3 = 200k\Omega$$

We use a series configuration of R_{1F} and R_1 (pot) (Fixed)

$$R_1 \text{ (pot)}: R_1 = 100k \text{ pot}$$

$$\text{Minimum gain} = 0.5 \left(1 + \frac{R_2}{R_{1F}}\right) = 0.5 \left(1 + \frac{R_2}{100k + R_1}\right)$$

$$\text{If } A_d \leq 100 \Rightarrow 1 = 0.5 \left(1 + \frac{2R_2 R_1}{R_{1F} + 100k}\right)$$

$$\Rightarrow R_{1F} + 100 = 2R_2 \quad (1)$$

$$\text{Maximum gain} = 100 = 0.5 \left(1 + \frac{R_2}{R_{1F}/2}\right) \Rightarrow$$

$$2R_2 = 199 R_{1F} \quad (2)$$

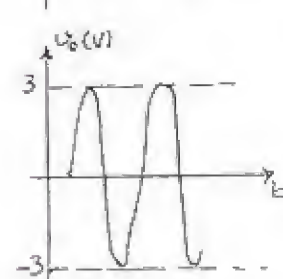
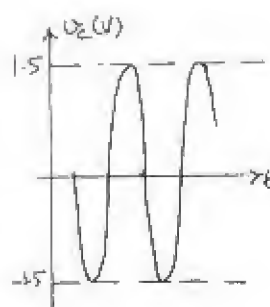
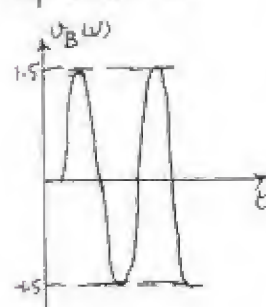
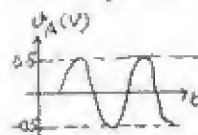
$$(1), (2) \Rightarrow R_{1F} = 0.505 k\Omega \approx 0.5 k\Omega$$

$$R_2 = 50.25 k\Omega \approx 50 k\Omega$$

2.77

$$a) \frac{v_B}{v_A} = 1 + \frac{20}{10} = 3 \frac{V}{V}, \frac{v_C}{v_A} = -\frac{30}{10} = -3 \frac{V}{V}$$

$$b) v_o = v_B - v_C = 6 v_A \Rightarrow \frac{v_o}{v_A} = 6 \frac{V}{V}$$



c) v_B and v_C can be $\pm 1V$ or $28V$ P-P.

$$-28 \leq v_o \leq 28 \text{ or } 56 \text{ p.p.}$$

$$v_{rms} = \frac{19.8 V}{\sqrt{2}} = \frac{28}{\sqrt{2}}$$

2.78

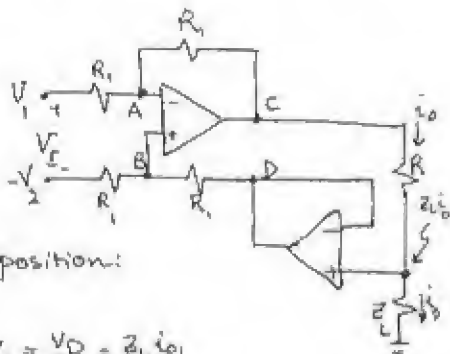
Refer to Fig. P.2.78.a:

Since the inputs of the op-amp don't draw any current, V_E appears across R_1 .

$$i_o = \frac{V_E}{R_1}$$

Fig. P.2.78.B

$$V_D = Z_L i_o$$



We use superposition:

$$V_E = V_1 - V_2$$

$$V_1 \text{ only: } V_D = \frac{V_D}{2} = \frac{Z_L i_o}{2}$$

$$\frac{V_1 - \frac{Z_L i_o}{2}}{R_1} = \frac{Z_L i_o - i_o (Z_L + R_1)}{R_1}$$

$$\Rightarrow V_1 = i_o R_1 \Rightarrow i_o = \frac{V_1}{R_1}$$

Now if only $(-V_2)$ is applied:

$$V_D = \frac{-V_2 + Z_L i_o}{2}, \quad V_A = \frac{i_o \times (R_1 + Z_L)}{2}$$

$$V_A = V_D \Rightarrow -V_2 + Z_L i_o = i_o R_1 + i_o Z_L$$

$$-V_2 = i_o R_1 \Rightarrow i_o = \frac{-V_2}{R_1}$$

The total current due to both sources is:

$$i_o = i_{o1} + i_{o2} = \frac{V_1}{R_1} - \frac{V_2}{R_1} = \frac{V_E}{R_1}$$

The circuit in Figure P.2.78(a) has ideally infinite input resistance, and it requires that both terminals of Z_L be available, while the other circuit has finite input resistance with one side of Z_L grounded.

2.79

A_o	f_b (Hz)	f_c (Hz)	eq. 2.28:
10^5	10^2	10^7	$\omega_b = A_o \omega_b$
10^6	1	10^6	$\Rightarrow f_c = A_o f_b$
10^5	10^3	10^8	
10^7	10^1	10^6	
2×10^5	10	2×10^6	

2.80

$$\text{Eq. 2.25: } A = \frac{A_o}{1 + j\omega/\omega_b} \Rightarrow |A| = \frac{|A_o|}{\sqrt{1 + (\frac{f}{f_b})^2}}$$

$$A_o = 86 \text{ dB}, \quad A = 40 \text{ dB} @ f = 100 \text{ kHz}$$

$$20 \log \sqrt{1 + (\frac{f}{f_b})^2} = 20 \log \frac{|A_o|}{|A|} = 20 \log A_o - 20 \log A$$

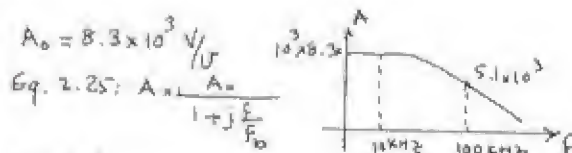
$$= 86 - 40 = 46 \text{ dB}$$

$$1 + (\frac{100 \text{ kHz}}{f_b})^2 = (199.5)^2 \Rightarrow f_b = 0.501 \text{ kHz}$$

$$f_b = 501 \text{ Hz}$$

$$f_c = A_o f_b = 1.995 \times 10^4 \times 501 = 9.998 \text{ MHz} \approx 10 \text{ MHz}$$

2.81



$$\text{Eq. 2.25: } A = \frac{A_o}{1 + j\frac{f}{f_b}}$$

$$f_c = A_o f_b$$

$$5.1 \times 10^3 = \frac{8.3 \times 10^3}{\sqrt{1 + (\frac{100 \text{ kHz}}{f_b})^2}} \Rightarrow 1 + (\frac{100 \text{ kHz}}{f_b})^2 = 2.65$$

$$f_b = 60.7 \text{ kHz}$$

$$f_c = A_o f_b = 8.3 \times 10^3 \times 60.7 = 503 \text{ MHz}$$

2.82

We have:

$$A_o = 20 \text{ dB} + A_{(dB)} \quad 20 \text{ dB} = 20 \log 10 \Rightarrow A_o = 10, A$$

$$a) A_o = 10 \times 3 \times 10^5 = 3 \times 10^6 \text{ Hz } \sqrt{V/V}$$

$$A = \frac{A_o}{1 + j\frac{f}{f_b}} \Rightarrow |1 + j\frac{f}{f_b}| = \frac{A_o}{A} = 10 \Rightarrow \frac{3 \times 10^6}{f_b} = \sqrt{99}$$

$$\Rightarrow f_b = 60.3 \text{ Hz}$$

$$f_c = A_o f_b = 3 \times 10^6 \times 60.3 = 180.9 \text{ MHz}$$

$$b) A = 50 \times 10^5 \sqrt{V/V} \Rightarrow A_o = 10 \times 50 \times 10^5 = 50 \times 10^6 \sqrt{V/V}$$

$$|1 + j\frac{f}{f_b}| = \frac{A_o}{A} = 10 \Rightarrow \frac{10^7}{f_b} = \sqrt{99} \Rightarrow f_b = 1 \text{ Hz}$$

$$f_c = A_o f_b = 50 \text{ MHz}$$

$$c) A = 1500 \sqrt{V/V} \Rightarrow A_o = 15000 \sqrt{V/V}$$

Cont.

$$\left|1 + \frac{jF}{f_b}\right| = 10 \Rightarrow \frac{0.1 \times 10^6}{f_b} = \sqrt{99} \Rightarrow f_b = 10 \text{ kHz}$$

$$f_c = 15000 \times 10^3 = 150 \text{ MHz}$$

$$d) A_v = 10 \times 100 = 1000 \text{ V/V}$$

$$\left|1 + \frac{jF}{f_b}\right| = 10 \Rightarrow \frac{0.1 \times 10}{f_b} = \sqrt{99} \Rightarrow f_b = 10 \text{ MHz}$$

$$f_c = 1000 \times 10 \text{ MHz} = 100 \text{ MHz}$$

$$e) A_v = 25 \text{ V/V} \times 10 = 25 \times 10^4 \text{ V/V}$$

$$\left|1 + \frac{jF}{f_b}\right| = 10 \Rightarrow \frac{25 \text{ kHz}}{f_b} = \sqrt{99} \Rightarrow f_b = 2.51 \text{ kHz}$$

$$f_c = A_v f_b = 25 \times 10^4 \times 2.51 \times 10^3 = 627.5 \text{ MHz}$$

2.83

$$G_{nom} = -\frac{R_2}{R_1} = -20 \quad A_v = 10^4 \text{ V/V} \quad f_b = 10^6 \text{ Hz}$$

$$\text{Eq. 2.35: } \omega_{3db} = \frac{\omega_b}{1 + R_2/R_1} = \frac{2\pi \times 10^6}{1 + 20} = 2\pi \times 47.6 \text{ kHz}$$

$$f_{3db} = 47.6 \text{ kHz}$$

$$\text{Eq. 2.34: } \frac{V_o}{V_i} = \frac{-R_2/R_1}{1 + \frac{s}{\omega_b/(1+R_2/R_1)}} = \frac{-20}{1 + \frac{21.5}{2\pi \times 10^6} s}$$

$$F = 0.1 f_{3db} \Rightarrow \left|\frac{V_o}{V_i}\right| = \frac{-20}{\sqrt{1 + (0.1)^2}} = 19.9 \text{ V/V}$$

$$F = 10 f_{3db} \Rightarrow \left|\frac{V_o}{V_i}\right| = \frac{-20}{\sqrt{1 + 100}} = 1.99 \text{ V/V}$$

2.84

$$1 + \frac{R_2}{R_1} = 100 \text{ V/V} \quad f_c = 20 \text{ MHz}$$

$$f_{3db} = \frac{f_c}{1 + \frac{R_2}{R_1}} = 200 \text{ kHz}$$

$$G(j\omega) = \frac{100}{1 + j f/f_{3db}} \Rightarrow \phi = -\tan^{-1} \frac{f}{f_{3db}}$$

$$\phi = -6^\circ \Rightarrow f = f_{3db} \times \tan 6^\circ = 21 \text{ kHz}$$

$$\phi = -84^\circ \Rightarrow f = f_{3db} \times \tan 84^\circ = 1.9 \text{ MHz}$$

2.85

$$a) -\frac{R_2}{R_1} = -100 \text{ V/V} \quad f_{3db} = 100 \text{ kHz}$$

$$\text{Eq. 2.35: } \omega_c = \omega_{3db} \left(1 + \frac{R_2}{R_1}\right) \Rightarrow f_c = 100 \times 101 = 101 \text{ MHz}$$

$$b) 1 + \frac{R_2}{R_1} = 100 \text{ V/V} \quad f_{3db} = 100 \text{ kHz}$$

$$f_c = f_{3db} \left(1 + \frac{R_2}{R_1}\right) = 10 \text{ MHz}$$

$$c) 1 + \frac{R_2}{R_1} = 2 \text{ V/V} \quad f_{3db} = 10 \text{ MHz}$$

$$f_c = 10 \text{ MHz} \times 2 = 20 \text{ MHz}$$

$$d) -\frac{R_2}{R_1} = -2 \text{ V/V} \quad f_{3db} = 10 \text{ MHz}$$

$$f_c = 10 \text{ MHz} (1+2) = 30 \text{ MHz}$$

$$e) -\frac{R_2}{R_1} = -1000 \text{ V/V} \quad f_{3db} = 20 \text{ kHz}$$

$$f_c = 20 \times (1+1000) = 20.02 \text{ MHz}$$

$$f) 1 + \frac{R_2}{R_1} = 1 \text{ V/V} \quad f_{3db} = 1 \text{ MHz}$$

$$f_c = 1 \times 1 = 1 \text{ MHz}$$

$$g) -\frac{R_2}{R_1} = -1 \quad f_{3db} = 1 \text{ MHz}$$

$$f_c = 1 \text{ M} (1+1) = 2 \text{ MHz}$$

2.86

$$1 + \frac{R_2}{R_1} = 100 \text{ V/V} \quad f_{3db} = 8 \text{ kHz}$$

$$f_c = 8 \times 100 = 800 \text{ kHz}$$

$$\text{for } f_{3db} = 20 \text{ kHz: } G_o = \frac{800}{20} = 40 \text{ V/V}$$

2.87

$$f_{3db} = f_c = 1 \text{ MHz}$$

$$|G| = \frac{1}{\sqrt{1 + \left(\frac{f}{f_{3db}}\right)^2}} = \frac{1}{\sqrt{1 + F^2}} \quad F \text{ in MHz}$$

$$|G| = 0.99 \Rightarrow F = 0.142 \text{ MHz}$$

The follower behaves like a low-pass STC circuit with a time constant $\tau = \frac{1}{\omega_{3db}}$

$$\text{Thus: } \tau = \frac{1}{2\pi \times 10^6} = \frac{1}{2\pi} \mu\text{s}$$

$$t_r = 2.2\tau = 0.35 \mu\text{s} \quad (\text{Refer to Appendix F})$$

2.88

$$1 + \frac{R_2}{R_1} = 10 \text{ V/V} \quad A_1 = 1 \text{ K}\Omega \quad R_2 = 9 \text{ K}\Omega$$

If we consider 5τ the time that it takes for the output voltage to reach 99% of its final value, then: $5\tau = 100 \text{ ns} \Rightarrow \tau = 20 \text{ ns}$
 $\tau = \frac{1}{\omega_{3db}} \Rightarrow \omega_{3db} = 50 \times 10^6 \Rightarrow f_{3db} = 7.96 \text{ MHz}$
 $f_t = (1 + \frac{R_2}{R_1}) f_{3db} = 10 \times 7.96 = 79.6 \text{ MHz}$

2.89

a) Assume two identical stages, each with a gain function:

$$G = \frac{G_0}{1 + j \frac{f}{f_1}} = \frac{G_0}{1 + j f/f_1}$$

$$G = \frac{G_0}{\sqrt{1 + (\frac{f}{f_1})^2}}$$

Overall gain of the cascade is $\frac{G_0^2}{1 + (\frac{f}{f_1})^2}$

The gain will drop by 3db when:

$$1 + (\frac{f_{3db}}{f_1})^2 = \sqrt{2}, \text{ Note } 3\text{db} = 20 \log \sqrt{2}$$

$$f_{3db} = f_1 \sqrt{\sqrt{2} - 1}$$

b) $40\text{db} = 20 \log G_0 \Rightarrow G_0 = 100 = 1 + \frac{R_2}{R_1}$
 $f_{3db} = \frac{f_t}{1 + \frac{R_2}{R_1}} = \frac{1 \text{ MHz}}{100} = 10 \text{ KHz}$

c) Each stage should have 20db gain or $1 + \frac{R_2}{R_1} = 10$ and therefore a 3db frequency of: $f_1 = \frac{10^6}{10} = 10^5 \text{ Hz}$.
 The overall $f_{3db} = 10^5 \sqrt{\sqrt{2} - 1} = 64.35 \text{ KHz}$
 which is 6 times greater than the bandwidth achieved using single op-amp (case b above)

2.90

$$f_t = 100 \times 5 = 500 \text{ MHz} \text{ - if single op-amp is used.}$$

with op-amp that has only $f_t = 40 \text{ MHz}$, the possible closed loop gain at 5MHz is:

$$A = \frac{40}{5} = 8 \text{ V/V}$$

To obtain an overall gain of 100, three such amplifiers cascaded, would be required.

Now, if each of the 3 stages, has a low-frequency (d) closed loop gain K , then its 3db frequency will be $\frac{40}{K} \text{ MHz}$. Thus for each stage the closed loop gain is: $|G| = \frac{K}{\sqrt{1 + (\frac{f}{\frac{40}{K}})^2}}$

which at $f = 5 \text{ MHz}$ becomes:

$$|G_{5\text{MHz}}| = \frac{K}{\sqrt{1 + (\frac{5}{\frac{40}{K}})^2}}$$

The overall gain of 100: $100 = \left[\frac{K}{\sqrt{1 + (\frac{5}{\frac{40}{K}})^2}} \right]^3$

$$K = 5.7$$

Thus for each cascade stage: $f_{3db} = \frac{40}{5.7}$
 $f_{3db} = 7 \text{ MHz}$

The 3-db frequency of the overall amplifier, f_1 , can be calculated as:

$$\left[\frac{5.7}{\sqrt{1 + (\frac{f}{7})^2}} \right]^3 = \frac{(5.7)^3}{\sqrt{2}} \Rightarrow f_1 = 3.6 \text{ MHz}$$

2.91

a) $\frac{R_2}{R_1} = K \quad f_{3db} = \frac{f_t}{1 + \frac{R_2}{R_1}} = \frac{f_t}{1+K}$
 $\text{GBP} = \text{Gain} \times f_{3db}$
 $\text{GBP} = K \frac{f_t}{1+K}$

b) $1 + \frac{R_2}{R_1} = K \quad f_{3db} = \frac{f_t}{K}$
 $\text{GBP} = K \frac{f_t}{K} = f_t$

The non-inverting amplifier realizes a higher GBP and it's independent of K .

2.92

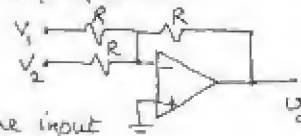
To find f_{3db} we use superposition:

Set $V_2 = 0$

Now using Thevenin's

Theorem to simplify the input

circuit results in:



Cont.

$$\frac{V_o}{V_{i/2}} = \frac{-R/R_{i2}}{1 + 5 \frac{1+R/R_{i2}}{w_k}}$$

which gives:

$$\frac{V_o}{V_i} = \frac{-1}{1 + 5/(w_k/3)}$$

$f_{3dB} = \frac{f_c}{3}$. Similar results can be obtained for $\frac{V_o}{V_i}$.



Theremin's equivalent

2.93

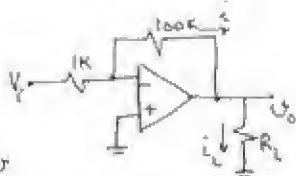
The peak value of the largest possible sine wave that can be applied at the input without output clipping is: $\frac{\pm 12V}{100} = \pm 0.12V = 120mV$
rms value = $\frac{120}{\sqrt{2}} = 85mV$

2.94

a) $R_L = 1k\Omega$

for $V_{omax} = 10V$: $V_p = \frac{10}{100}$
 $V_p = 0.1V$

when output is at its peak, $i_L = \frac{10}{1k} = 10mA$
 $i = \frac{10}{100k} = 0.1mA$. therefore $i_o = 10 + 0.1 = 10.1mA$
is well under $i_{omax} = 20mA$.



b) $R_L = 100\Omega$

If output is at its peak: $i_L = \frac{10V}{0.1} = 100mA$
which exceeds $i_{omax} = 20mA$. Therefore V_o cannot go as high as $10V$. instead:

$$20mA = \frac{V_o}{100\Omega} + \frac{V_o}{100k} \Rightarrow V_o = \frac{20}{100.1} = 2V$$

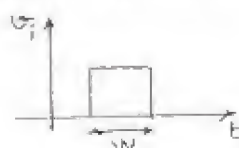
$$V_p = \frac{2}{100} = 0.02V = 20mV$$

c) $R_L = ?$ $i_{omax} = 20mA = \frac{10V}{R_{min}} + \frac{10V}{100k}$
 $20 - 0.1 = \frac{10}{R_{min}} \Rightarrow R_{min} = 502\Omega$

2.95

The output is triangular with the slew rate

of $20V/\mu s$. In order to reach $3V$, it takes $\frac{3}{20} \mu s = 0.15 \mu s = 150ns$. Therefore the minimum pulse width is $150ns$.



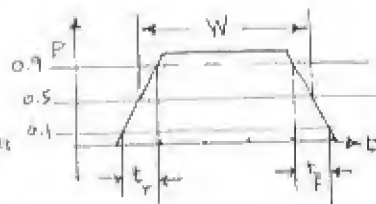
2.96

$W = 2\mu s$

$$t_r = t_f = 0.2W = 0.4\mu s$$

$$t_r = t_f = 0.2\mu s$$

$$SR = \frac{(0.9 - 0.1)P}{t_r} = \frac{0.8 \times 10}{0.2} = 40V/\mu s$$



2.97

Slope of the triangle wave = $\frac{20V}{T/2} = SR$

$$\text{Thus } \frac{20}{T} \times 2 = 10V/\mu s$$

$$\Rightarrow T = 4\mu s \text{ or } f = \frac{1}{T} = 250kHz$$

For a sine wave $V_o = \hat{V}_o \sin(2\pi \times 250 \times 10^3 t)$

$$\left. \frac{dV_o}{dt} \right|_{max} = 2\pi \times 250 \times 10^3 \hat{V}_o = SR$$

$$\Rightarrow \hat{V}_o = \frac{10 \times 10^6}{2\pi \times 10^3 \times 250} = 6.37V$$

2.98

$$V_o = 10 \sin \omega t \Rightarrow \frac{dV_o}{dt} = 10\omega \cos \omega t \Rightarrow \left. \frac{dV_o}{dt} \right|_{max} = 10\omega$$

The highest frequency at which this wave

output is possible is that for which:

$$\left. \frac{dV_o}{dt} \right|_{max} = SR \Rightarrow 10\omega_{max} = 60 \times 10^6 = \omega_{max} = 6 \times 10^6$$

$$\Rightarrow f_{max} = 45.5kHz$$

2.99

a) $V_i = 0.5$, $V_o = 10 \times 0.5 = 5V$

Cont.

output distortion will be due to slew rate limitation and will occur at the frequency for which $\left. \frac{dv_o}{dt} \right|_{\max} = SR$

$$\omega_{\max} \times 5 = \frac{1}{10^{-6}} = 2 \times 10^5 \text{ rad/s} \Rightarrow f_{\max} = 31.8 \text{ KHz}$$

b) The output will distort at the value of V_i that results in $\left. \frac{dv_o}{dt} \right|_{\max} = SR$.

$$V_o = 10 V_i \sin 2\pi \times 20 \times 10^3$$

$$\left. \frac{dv_o}{dt} \right|_{\max} = 10 V_i \times 2\pi \times 20 \times 10^3$$

$$\text{Thus } V_i = \frac{1/10^{-6}}{10 \times 2\pi \times 20 \times 10^3} = 0.795 \text{ V}$$

$$\text{c) } V_i = 50 \text{ mV } V_o = 500 \text{ mV} = 0.5 \text{ V}$$

Slew rate begins at the frequency for which $\omega \times 0.5 = SR$

$$\text{which gives } \omega = \frac{1/10^{-6}}{0.5} = 2 \times 10^6 \text{ rad/s or } f = 318.3 \text{ KHz}$$

However the small signal 3db frequency is

$$f_{3db} = \frac{f_0}{1 + \frac{R_2}{R_1}} = \frac{2 \times 10^6}{10} = 200 \text{ KHz}$$

Thus the useful frequency range is limited at 200 KHz.

d) for $f = 5 \text{ KHz}$, the slew rate limitation occurs at the value of V_i given by

$$\omega \times 10 V_i = SR \Rightarrow V_i = \frac{1/10^{-6}}{2\pi \times 5 \times 10^3 \times 10} = 3.18 \text{ V}$$

Such an input voltage, however would ideally result in an output of 31.8V which exceeds V_{omax} . Thus $V_{\text{imax}} = \frac{V_{\text{omax}}}{10} = 1 \text{ V peak}$.

2.102

Output DC offset, $V_{os} = 3 \text{ mV} \times 1000 = 3 \text{ V}$

Therefore the maximum amplitude of an input sinusoid is the one that results in an output peak amplitude of $13 - 3 = 10 \text{ V} \Rightarrow V_i = \frac{10}{1000} = 10 \text{ mV}$

If the amplifier is capacity coupled, then:

$$V_{i\max} = \frac{13}{1000} = 13 \text{ mV}$$

2.103

$$V_{os} = \frac{1.4}{100} = 1.4 \text{ mV}$$



2.104

$$\text{a) } I_B = (I_{B1} + I_{B2})/2$$

open input:

$$V_o = V_i + R_2 I_{B1} = V_{os} + R_2 I_{B1}$$

$$9.31 = V_{os} + 10000 I_{B1} \quad (1)$$

input connected to ground:

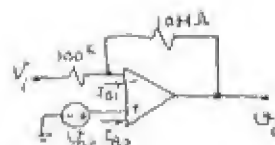
$$V_o = V_i + R_2 (I_{B1} + \frac{V_{os}}{R_1}) = V_{os} (1 + \frac{R_2}{R_1}) + R_2 I_{B1}$$

$$9.09 = V_{os} \times 101 + 10000 I_{B1} \quad (2)$$

$$(1), (2) \Rightarrow 100 V_{os} = -0.22 \Rightarrow V_{os} = -2.2 \text{ mV}$$

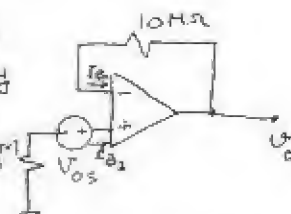
$$\Rightarrow I_{B1} = 930 \text{ nA}$$

$$I_B \approx I_{B1} = 930 \text{ nA}$$



$$\text{b) } V_{os} = -2.2 \text{ mV}$$

c) In this case, since R_1 is too large, we may ignore V_{os} compare to the voltage drop across R_1 .



$V_{os} \ll R_1 I_B$, Also Eq. 2.46 holds, $R_3 = R_1 \parallel R_2$ therefore from Eq. 2.47: $V_o = I_{B1} R_2 \Rightarrow I_{B1} = \frac{0.8}{10^4}$

$$I_{B1} = -80 \text{ nA}$$

2.100

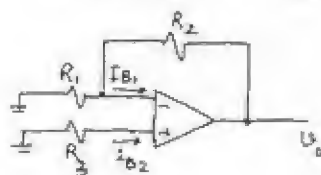
$$V_o = V_{os} (1 + \frac{R_2}{R_1}) \Rightarrow -0.3 = V_{os} (1 + \frac{100}{1}) \approx 3 \text{ mV}$$

2.101

$$V_{os} = \pm 2 \text{ mV}$$

$$V_o = 0.01 \sin \omega t \times 200 + V_{os} \times 200 = 2 \sin \omega t \pm 0.4 \text{ V}$$

2.105



$$R_2 = 100k\Omega$$

$$R_1 = \frac{100k\Omega}{9}$$

$$R_3 = 5k\Omega$$

$$I_{B1} = 1 \pm 0.05 \mu A, V_{OS} = 0$$

$$I_{B2} = 1 \mp 0.05 \mu A$$

From Eq. 2.45: $V_0 = -I_{B2}R_3 + R_2(I_{B1} - I_{B2}\frac{R_2}{R_1})$

For $I_{B1} = 1.05 \mu A, I_{B2} = 0.95 \mu A$

$$V_0 = -0.95 \times 5 + 100(1.05 - 0.95 \times \frac{5}{100} \times 9) = 57.5 mV$$

b) For $I_{B1} = 0.95 \mu A, I_{B2} = 1.05 \mu A$

$$V_0 = -1.05 \times 5 + 100(0.95 - 1.05 \times \frac{5}{100} \times 9) = 42.5 mV$$

$$\Rightarrow 42.5 mV \leq V_0 \leq 57.5 mV$$

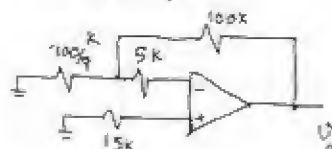
From the discussion in the text we know that to minimize the DC output voltage resulting from the input bias current, we should make the total DC resistance in the inputs of the op-amp equal. Currently, the negative input sees a resistance of $R_1 \parallel R_2 = \frac{100}{9} \parallel 100 = 10k\Omega$ while the positive input terminal sees $5k\Omega$ source resistance. Therefore we should add $5k\Omega$ series resistor to the positive input terminal to make the effective resistance $5k\Omega + 5k\Omega = 10k\Omega$. The resulting V_0 can be found as follows:

$$V_0 = -I_{B2} \times 10 + 100(I_{B1} - I_{B2} \frac{10}{100/9}) = (I_{B1} - I_{B2}) \times 100$$

$$V_0 = I_{OS} \times 100 = \pm 0.1 \times 100 = \pm 10 mV$$

$$V_0 = 10 mV$$

If the signal source resistance is $15k\Omega$, then the resistances can be equalized by adding a $5k\Omega$ resistor in series with the negative input load of the op-amp.



2.106

$$R_2 = R_3 = 100k\Omega$$

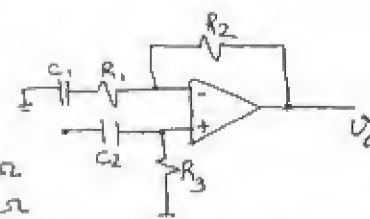
$$1 + \frac{R_2}{R_1} = 200$$

$$R_1 = \frac{100k}{199} = 502\Omega$$

$$R_1 = \frac{100k}{199} \approx 500\Omega$$

$$\frac{1}{R_1 C_1} = 2\pi \times 100 \Rightarrow C_1 = \frac{1}{500 \times 2\pi \times 100} = 3.18 \mu F$$

$$\frac{1}{R_2 C_2} = 2\pi \times 10 \Rightarrow C_2 = \frac{1}{100 \times 2\pi \times 10} = 0.16 \mu F$$



2.107

The output component due to V_{OS} is:

$$V_{O1} = V_{OS} (1 + \frac{1M}{10k})$$

$$V_{O1} = 4(1+100) = 404 mV$$

The output component due to I_B or input bias current is:

$$I_{B1} = I_B + \frac{I_{OS}}{2}, I_{B2} = I_B - \frac{I_{OS}}{2}$$

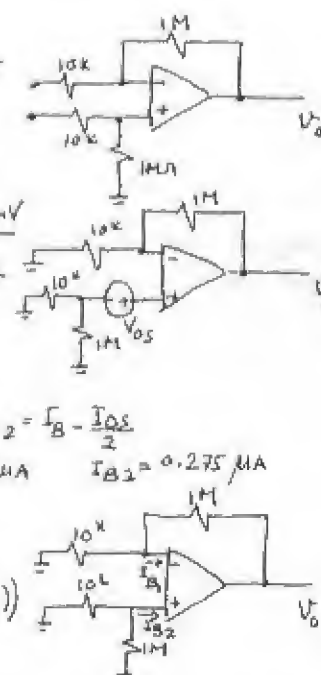
$$I_{B1} = 0.3 + \frac{0.05}{2} = 0.325 \mu A, I_{B2} = 0.275 \mu A$$

$$V_+ = -I_{B2} \times (10k \parallel 1M)$$

$$V_+ = -2.72 mV$$

$$V_{O2} = V_+ + (1M \times (C_1 + \frac{V_+}{10k}))$$

$$V_{O2} = 50 mV$$



The worst case (largest) DC offset voltage at the output is $404 + 50 = 454 mV$

2.108

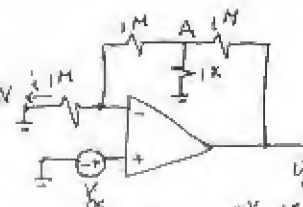
$$V_+ = V_- = V_{OS} \Rightarrow V_A = 2V_{OS} = 8 mV$$

$$I = \frac{V_{OS}}{1M} = V_{OS} (\mu A)$$

$$V_0 = V_A + 1M \times (I + \frac{V_A}{1k})$$

$$V_0 = 2V_{OS} + 1M (\frac{V_{OS}}{1M} + \frac{2V_{OS}}{1k}) = 2003V_{OS} = 2003 \times 4 = 8 V$$

$$V_0 = 8 V$$



Cont.

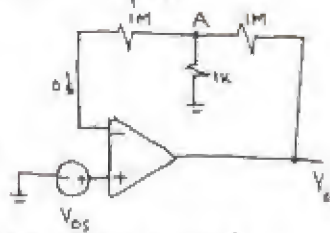
for capacitively coupled input:

$$V_+ = V_- = V_{os}$$

$$V_A = V_{os}$$

$$V_o = V_A + 1M \times \frac{V_{os}}{1K}$$

$$V_o = 1001 V_{os} = +4.004V$$



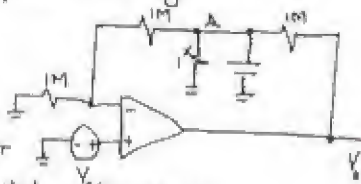
for capacitively coupled 1K to ground:

$$V_+ = V_- = V_{os}$$

$$V_A = 2V_{os}$$

$$V_o = 3V_{os} = +12mV$$

This is much smaller than capacitively coupled input case.



2.109

At $0^\circ C$, we expect $\pm 10 \times 25 \times 1000^\mu = \pm 250mV$

At $75^\circ C$, we expect $\pm 10 \times 50 \times 1000^\mu = \pm 500mV$

We expect these quantities to have opposite polarities.

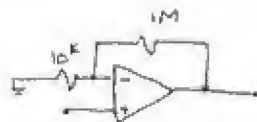
2.110

$$100 = 1 + \frac{R_2}{R_1} \Rightarrow R_2 = 10.1K\Omega$$

$$a) V_o = 100 \times 10^{-9} \times 1 \times 10^6 = 0.1V$$

b) Largest output offset is:

$$V_o = 1mV \times 100 + 0.1V = 200mV = 0.2V$$



c) For bias current compensation we connect a resistor R_3 in series with the positive input terminal of the op-amp, with: $R_3 = R_1 \parallel R_2$

$$I_{os} = \frac{100}{10} = 10nA$$

$$R_3 = 10K \parallel 10.1M = 10K\Omega$$

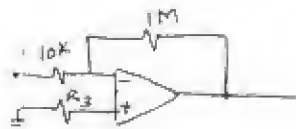
The offset current alone results in an output offset voltage of $I_{os} \times R_2 = 10 \times 10^{-9} \times 1 \times 10^6 = 10mV$

$$d) V_o = 100mV + 10mV = 110mV$$

2.111

$$R_3 = R_1 \parallel R_2 = 9.9K\Omega$$

(Refer to 2.46)

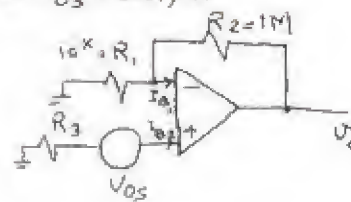


$$V_o = I_{os} R_2 \quad \text{Eq. 2.47}$$

$$V_o = 0.21 = I_{os} \times 1M \Rightarrow I_{os} = 0.21\mu A$$

$$\text{If } V_{os} = 1mV$$

$$V_+ = -\frac{I_{os} R_3}{3} V_{os}$$



$$I_{B1} = \frac{R_2 I_{B2} \pm V_{os}}{R_1} + \frac{0.21 + R_2 I_{B2} \pm V_{os}}{R_2}$$

$$I_{B1} = R_2 I_{B2} \left(\frac{1}{R_1} + \frac{1}{R_2} \right) \pm V_{os} \left(\frac{1}{R_1} + \frac{1}{R_2} \right)$$

$$\frac{1}{R_3} = \frac{1}{R_1} + \frac{1}{R_2} \Rightarrow I_{B1} - I_{B2} = \pm V_{os} \left(\frac{1}{R_1} + \frac{1}{R_2} \right)$$

$$\Rightarrow I_{os} = \pm \frac{1mV}{9.9K} = \pm 0.1\mu A$$

If we apply the same current as I_{os} to the other end of R_3 , then it will cancel out the offset current effect on the output. $\pm 0.1\mu A$

Now if we use $\pm 15V$ supplies:

2.112

$$\frac{V_o}{V_i} = \frac{-1}{sCR} = \frac{-1}{j\omega CR} = \frac{1}{-j\omega \times 10 \times 10^{-9} \times 100 \times 10^3}$$

$$\frac{V_o}{V_i} = -\frac{10^3}{j\omega}$$

$$a) \frac{V_o}{V_i} = 1 \Rightarrow \omega = 1 \times 10^3 \text{ rad/s} \Rightarrow f = 159Hz$$

b) $\frac{1}{j}$ indicates 90° lag, but since it's $-\frac{1}{j}$, it results in output leading the input by 90°

c) $\frac{V_o}{V_i} = -\frac{10^3}{j\omega}$ if frequency is lowered by a factor of 10, then the output would increase by a factor of 10.

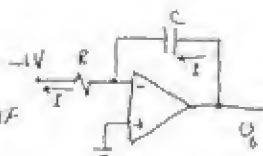
Cont.

d) The phase doesn't change and the output still leads the input by 90°

2.113

$$R_{in} = R = 100k\Omega$$

$$CR = 15 \Rightarrow C = \frac{1}{100 \times 10^3} = 10nF$$



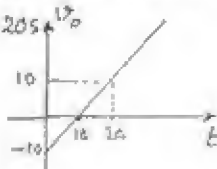
with a $-1V$ dc input applied, the capacitor charges with a constant current:

$I = \frac{1V}{R} = 0.01mA$ and its voltage rises linearly:

$$V_o(t) = -10 + \frac{1}{C} \int_0^t I dt = -10 + \frac{I}{C} t = -10 + \frac{t}{RC}$$

the voltage reaches $0V$ at $t = 10RC = 10s$

and it reaches $10V$ at $t = 20s$



2.114

$|T| = \frac{1}{\omega RC}$ If $|T| = 100V/V$ for $f = 1kHz$, then for $|T| = 1V/V$, f has to be $1k \times 100 = 100kHz$.

$$\text{Also } RC = \frac{1}{\omega T} = \frac{1}{2\pi \times 1k \times 100} = 1.59\mu s$$

2.115

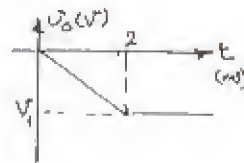
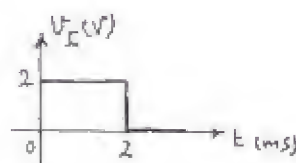
$R_{in} = R$, Thus $R = 100k\Omega$.

$$|T| = \frac{1}{\omega RC} = 1 \text{ at } \omega = \frac{1}{RC}$$

$$\omega = 1000 = \frac{1}{RC} \Rightarrow C = \frac{1}{1000 \times 100k} = 10nF$$

with a $2V$ - $2ms$ pulse at the input, the output falls linearly until $t = 2ms$ at which $V_o = V_i$, $V_o = \frac{-I}{C} t = \frac{-2}{RC} t = -2t$ Volts where t in ms

$$\text{Thus } V_o = -4V$$



with $V_i = 2\sin 1000t$ applied at the input,

$$V_o(t) = 2 \cdot \frac{1}{1000 \times 10^{-3}} \sin(1000t + 90^\circ)$$

$$V_o(t) = 2 \sin(1000t + 90^\circ)$$

2.116

$$R_{in} = R = 20k\Omega$$

$$|T| = \frac{1}{\omega RC} = 1 \text{ at } \omega = 2\pi \times 10^4 \text{ rad/s} \Rightarrow C = \frac{1}{2\pi \times 10^4 \times 20k} = 0.796nF$$

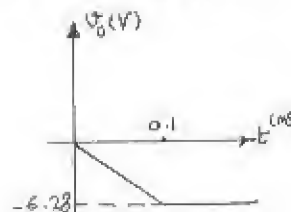
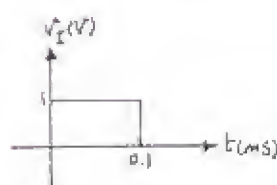
Refer to discussion in page 110:

$$\frac{V_o}{V_i} = \frac{R_F/R}{1 + sCR_F} \text{ and the finite dc gain is } \frac{-R_F}{R}. \text{ Therefore for } 40dB \text{ gain}$$

or equivalently $100V/V$ we have: $\frac{-R_F}{R} = -100V/V$

$$\Rightarrow R_F = 100 \times 20k = 2M\Omega$$

The corner frequency $\frac{1}{CR_F}$ is: $\frac{1}{0.796n \times 2M} = 628 \text{ Hz}$



a) when no R_F

$$V_o(t) = \frac{-1}{RC} \int_0^t 1 dt = -62.8t \text{ for } t \leq 0.1ms$$

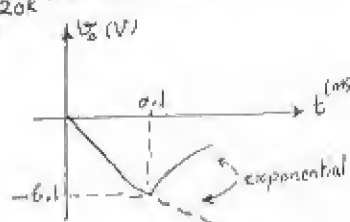
$$V_o(0.1) = -6.28V$$

b) with R_F : $V_o(t) = V_o(\infty) (1 - e^{-t/CR_F})$

(Refer to pg. 112)

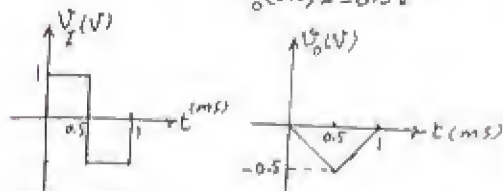
$$V_o(\infty) = -I \times R_F = -\frac{1V}{20k} \times 2M = -100V$$

$$V_o(t) = -100(1 - e^{-t/CR_F})$$



2.117

For $0 \leq t \leq 0.5 \text{ ms}$: $V_o(t) = V_o(0) - \frac{1}{RC} \int_0^t V_i dt$
 $V_o(t) = 0 - \frac{t}{RC} = -\frac{t}{1 \text{ ms}}$
 $V_o(0.5) = -0.5 \text{ V}$



For $0.5 \leq t \leq 1 \text{ ms}$: $V_o(t) = V_o(0.5) - \frac{1}{RC} \int_{0.5}^t -1 dt$
 $V_o(t) = -0.5 + \frac{1}{RC} (t - 0.5)$
 $V_o(1 \text{ ms}) = -0.5 + \frac{0.5}{1} = 0 \text{ V}$

Another way of thinking about this circuit is as follows:

For $0 \leq t \leq 0.5 \text{ ms}$ a current $I = \frac{V_i}{R}$ flows through R and C in the direction indicated on the diagram. At time t we write:

$$I \cdot t = -C \frac{dV_o}{dt} \Rightarrow V_o(t) = -\frac{I}{C} t = -\frac{1}{RC} t$$

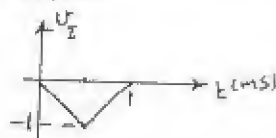
which indicates that the output voltage is linearly decreased, reaching -0.5 V at $t = 0.5 \text{ ms}$.

Then for $0.5 \leq t \leq 1 \text{ ms}$, the current flows in the opposite direction and V_o rises linearly reaching 0 V at $t = 1 \text{ ms}$.

For $V_i = \pm 2 \text{ V}$:

we obtain the

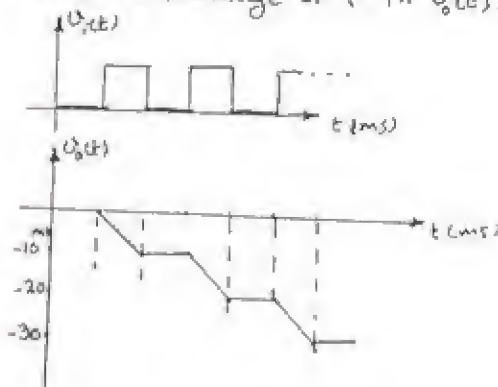
following waveform: (assuming time constant is the same)



If RC is also doubled, then the waveform becomes the same as the first case where $V_i = \pm 1 \text{ V}$ and $RC = 1 \text{ ms}$.

$$\Delta V_o = \frac{1}{RC} \int_0^{10 \text{ ms}} 1 \cdot dt = \frac{10 \mu\text{s}}{RC} = \frac{10 \mu\text{s}}{1 \text{ ms}} = 10 \text{ mV}$$

Therefore a total of 100 pulses are required to cause a change of 1 V in $V_o(t)$.



2.119

Refer to Fig. P2.119.

$$\frac{V_o}{V_i} = \frac{-Z_2}{Z_1} = -\frac{Y_1}{Y_2} = -\frac{1/R_1}{1/R_2 + sC} = -\frac{R_2/R_1}{1 + sCR_2}$$

which is an SRC LP circuit with a dc gain of $-\frac{R_2}{R_1}$ and a 3-db frequency $\omega_0 = \frac{1}{CR_2}$.

The input resistance equal to R_1 . So for:

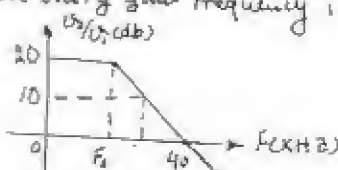
$R_1 = 1 \text{ k}\Omega \Rightarrow R_1 = 1 \text{ k}\Omega$ and for dc gain of 20 db or

$$10; \frac{R_2}{R_1} = 10 \Rightarrow R_2 = 10 \text{ k}\Omega$$

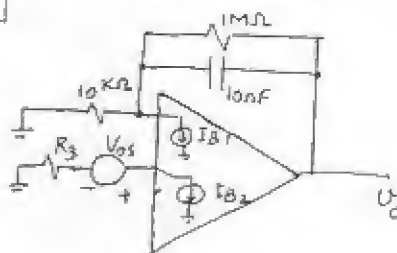
for 3db frequency of 4 kHz: $\omega_0 = 2\pi \times 4 \times 10^3 = \frac{1}{CR_2}$

$$\Rightarrow C = 4 \text{ nF}$$

the unity gain frequency is (0db) is 40 kHz



2.120

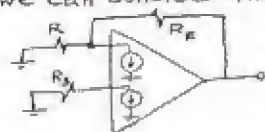


Cont.

2.118

Each pulse lowers the output voltage by:

a) To compensate for the effect of dc bias current I_B , we can consider the following model



Similar to the discussion leading to equation (2.46) we have: $R_3 = R \parallel R_F = 10k\Omega \parallel 1M\Omega \Rightarrow R_3 = 9.9k\Omega$

(b) As discussed in Section 2.8.2 the dc output voltage of the integrator when the input is grounded is: $V_o = V_{os} (1 + \frac{R_F}{R}) + I_{os} R_F$
 $V_o = 3mV (1 + \frac{1M\Omega}{10k\Omega}) + 10nA \times 1M\Omega = 0.303V + 0.01V$
 $V_o = 0.313V$

2.121

$$\frac{V_o}{V_i} = -sRC = -s \times 0.01 \times 10^{-6} \times 10 \times 10^3 = -10^{-4} s$$

$$\frac{V_o}{V_i}(j\omega) = -j\omega \times 10^{-4} \Rightarrow \left| \frac{V_o}{V_i} \right| = \omega \times 10^{-4}$$

$$\left| \frac{V_o}{V_i} \right| = 1 \text{ when } \omega = 10^4 \text{ Rad/s or } f = 1.59 \text{ kHz}$$

For an input 10 times this frequency, the output will be 10 times as large as the input: 10V peak-to-peak. The $(-j)$ indicates that the output lags the input by 90° . Thus $V_o(t) = -5 \sin(10^5 t + 90^\circ) \text{ V}$

2.122

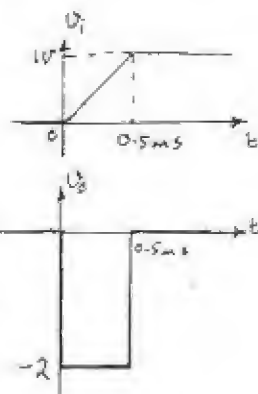
$$V_o = -RC \frac{dV_i}{dt}$$

therefore

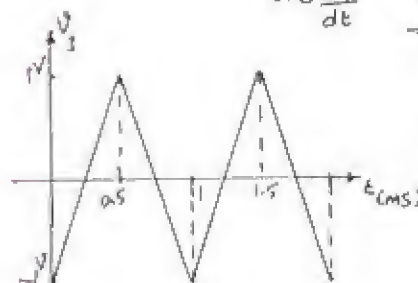
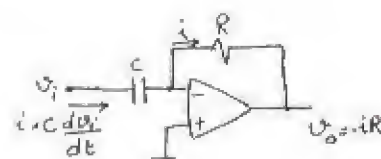
for $0 \leq t \leq 0.5$:

$$V_o = -1ms \times \frac{1V}{0.5ms} = -2V$$

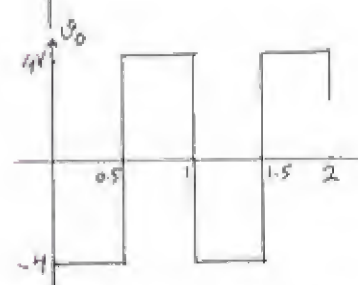
and $V_o = 0$ otherwise



2.123



$$\text{slope} = \frac{2V}{0.5ms} = 4 \frac{V}{ms}$$



$$C \frac{dV_i}{dt} = 0.1 \times 10^{-6} \times \frac{4}{10^{-3}} = 0.4 \text{ mA}$$

Thus the peak value of the output square wave is $0.4 \text{ mA} \times 10^4 \Omega = 4V$. The frequency of the output is the same as the input (1kHz).

The average value of the output is 0.

To increase the value of the output to 10V, R has to be increased to $\frac{10}{4} = 2.5$, i.e. $25k\Omega$.

When a 1-kHz, 1V peak input sine wave is applied

$$V_i = \sin(2\pi \times 1000t)$$

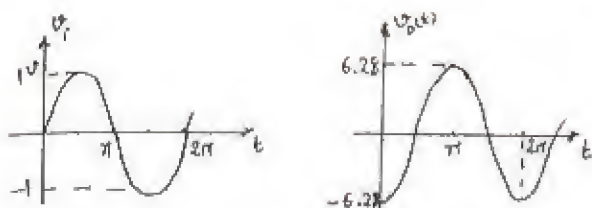
a sinusoidal signal appears at the output.

It can be determined by one of the following methods.

$$\begin{aligned} \text{a) } V_o(t) &= -RC \frac{dV_i}{dt} = -0.1 \times 10^{-6} \times 10 \times 10^3 \frac{dV_i}{dt} = -10 \frac{dV_i}{dt} \\ V_o(t) &= -10^{-3} \times 2\pi \times 1000 \times \cos(2\pi \times 1000t) \\ V_o(t) &= -2\pi \cos(2\pi \times 1000t) \end{aligned}$$

Thus the peak amplitude is 6.28V and the negative peaks occur at $t = 0, \frac{2\pi}{2\pi \times 1000}, \dots$

Cont.



$$b) \frac{V_o}{V_i} = -sRC \Rightarrow \frac{V_o}{V_i}(j\omega) = -j\omega RC \Rightarrow V_o(t) = -j\omega RC V_i(t)$$

the output is inverted and has 90° phase shift, due to $(-j)$ factor.

$$V_o(t) = -(wRC) \times 1 \sin(2\pi \times 1000t + 90^\circ)$$

$$V_o(t) = -6.28 \sin(2\pi \times 1000t + 90^\circ)$$

$$V_o(t) = -6.28 \cos(2\pi \times 1000t)$$

Same as before.

c) The peaks of the output waveform are equal to $RC \times (\text{maximum slope of input wave})$. Since the maximum slope occurs at the zero crossings, its value is $2\pi \times 1000$. Thus the peak output $= 2\pi \times 1000 \times RC = 6.28V$. The negative peak occurs at $\omega t = 0, 2\pi, \dots$

2.124

$$RC = 10^3 \text{ when } C = 10^{-6}F \Rightarrow R = 100K\Omega$$

$$\frac{V_o}{V_i} = -sRC \quad \frac{V_o}{V_i}(j\omega) = -j\omega RC \quad \angle = -90^\circ \text{ always}$$

$$\left| \frac{V_o}{V_i} \right| = 1 \Rightarrow \omega = \frac{1}{RC} = 10^3 \text{ rad/s} \quad \text{Gain is 10 times the unity}$$

gain, when the frequency is 10 times the unity gain frequency. Similarly for $\omega = \frac{1}{10} \text{ rad/s}$, gain is $0.1 V_o$. (for $\omega = 10 \text{ rad/s}$, gain $= 10 V_o$)

for high frequencies C is short-circuited.

$$\frac{V_o}{V_i} = -\frac{R}{R_1} = -100 \Rightarrow R_1 = 1K\Omega$$

$$\frac{V_o}{V_i} = \frac{-RCs}{R_1Cs + 1} = \frac{-10^3 s}{10^{-6}s + 1} \Rightarrow \omega_{3db} = 100 \text{ krads/s or } f = 15.9 \text{ kHz}$$

$$\text{for unity gain: } |10^3 s| = |10^{-6}s + 1| \Rightarrow \omega_H = 1.01 \text{ krads/s}$$

$$\text{if } \omega = 10.1 \text{ krads/s: } \left| \frac{V_o}{V_i} \right| = \frac{10.1}{1.01} = 10, \quad \angle = -95.77^\circ$$

2.125

Refer to Fig. P2.125:

$$\frac{V_o}{V_i} = -\frac{Z_2}{Z_1} = \frac{-R_2}{R_1 + \frac{1}{sC}} = \frac{-(R_2/R_1)s}{s + \frac{1}{R_1C}} \quad \text{which is the}$$

transfer function of an STC HP filter with a high frequency gain $K = -\frac{R_2}{R_1}$ and a 3-db frequency $\omega_0 = \frac{1}{R_1C}$.

The high-frequency input impedance approaches R_1 (as $\frac{1}{j\omega C}$ becomes negligibly small). So we can select $R_1 = 10K\Omega$.

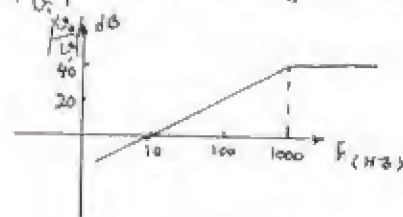
To obtain a high-frequency gain of 40dB (i.e. 100): $\frac{R_2}{R_1} = 100 \Rightarrow R_2 = 1M\Omega$.

For a 3-db frequency of 1000 Hz:

$$\frac{1}{R_1C} = 2\pi \times 1000 \Rightarrow C = 15.9 \text{ nF}$$

from the Bode-diagram below, we see that

$\left| \frac{V_o}{V_i} \right|$ reduces to unity at $F = 0.01 F_0 = 10 \text{ Hz}$



2.126

Refer to the circuit in Fig. P2.126:

$$\frac{V_o}{V_i} = -\frac{Z_2}{Z_1} = -\frac{1}{Z_1 Y_2} = -\frac{1}{(R_1 + \frac{1}{sC_1})(\frac{1}{R_2} + sC_2)}$$

$$\frac{V_o}{V_i} = -\frac{R_2 R_1}{(1 + \frac{1}{R_1 s C_1})(1 + s R_2 C_2)}$$

$$\frac{V_o}{V_i}(j\omega) = \frac{-R_2/R_1}{(1 + \frac{1}{j\omega R_1 C_1})(1 + j\omega R_2 C_2)} = \frac{-R_2/R_1}{(1 + \frac{j\omega_1}{j\omega})(1 + j\frac{\omega}{\omega_2})}$$

$$\text{where } \omega_1 = \frac{1}{R_1 C_1} \quad , \quad \omega_2 = \frac{1}{R_2 C_2}$$

a) for $\omega \ll \omega_1 \ll \omega_2$

$$\frac{V_o}{V_i}(j\omega) \approx \frac{-R_2/R_1}{(1 + \frac{j\omega_1}{j\omega})} \approx \frac{-R_2/R_1}{\omega_1/j\omega} = -j \frac{R_2}{R_1} \frac{\omega}{\omega_1}$$

Cont.

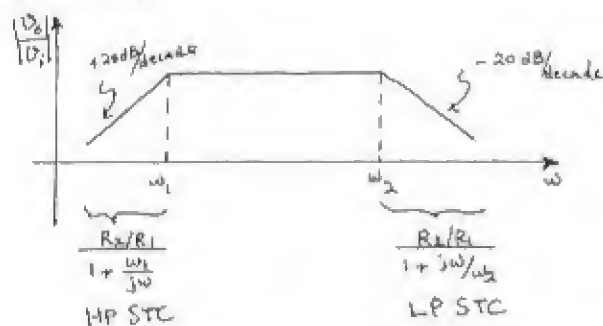
b) for $\omega_1 \ll \omega \ll \omega_2$

$$\frac{V_o}{V_i}(j\omega) \approx \frac{-R_2}{R_1}$$

c) for $\omega \gg \omega_2$ and $\omega_2 \gg \omega_1$:

$$\frac{V_o}{V_i}(j\omega) \approx \frac{-R_2/R_1}{1 + j\omega/\omega_2} \approx \frac{-R_2/R_1}{j\omega/\omega_2} = j\left(\frac{R_2}{R_1}\right)\left(\frac{\omega_2}{\omega}\right)$$

from the results of a), b) and c) we can draw the Bode-plot:



Design: $\frac{R_2}{R_1} = 1000$ (60dB gain in the mid-frequency range)

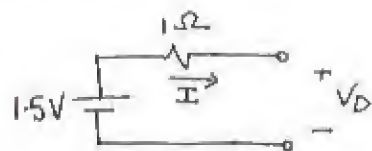
Req for $\omega \gg \omega_1$ $= R_1 = 1 \text{ k}\Omega \Rightarrow R_2 = 1 \text{ M}\Omega$

$$f_1 = 100 \text{ Hz} \Rightarrow \omega_1 = 2\pi \times 100 = \frac{1}{R_1 C_1} \Rightarrow C_1 = 1.59 \mu\text{F}$$

$$f_2 = 10 \text{ kHz} \Rightarrow \omega_2 = 2\pi \times 10 \times 10^3 = \frac{1}{R_2 C_2} \Rightarrow C_2 = 15.9 \text{ pF}$$

CHAPTER 3 - PROBLEMS

3.1



The diode can be reverse-biased and thus no current would flow, or forward-biased where current would flow.

(a) Reverse biased $I = 0A$ $V_D = 1.5V$

(b) Forward biased $I = 1.5A$ $V_D = 0V$

3.2

(a) Diode is conducting and thus has a 0V drop across it. Consequently

$$V = \underline{-3V}$$

$$I = \frac{3 - (-3)}{10k\Omega} = \underline{0.6mA}$$

(b) Diode is cut off.

$$V = \underline{3V} \quad I = \underline{0A}$$

(c) Diode is conducting

$$V = \underline{3V}$$

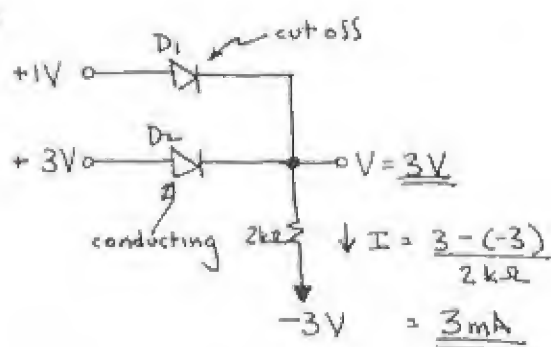
$$I = \frac{3 - (-3)}{10k\Omega} = \underline{0.6mA}$$

(d) Diode is cut off.

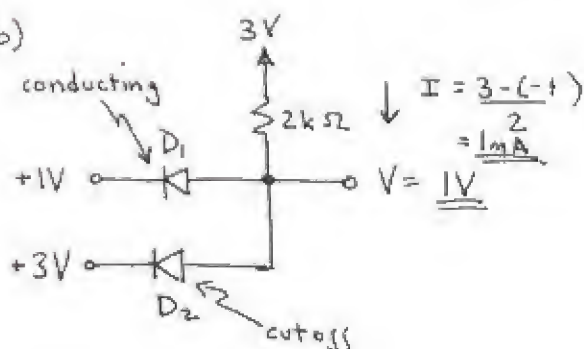
$$V = \underline{-3V} \quad I = \underline{0A}$$

3.3

(a)

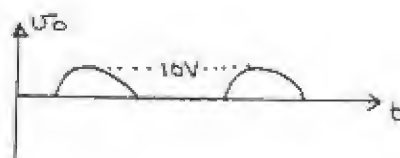


(b)



3.4

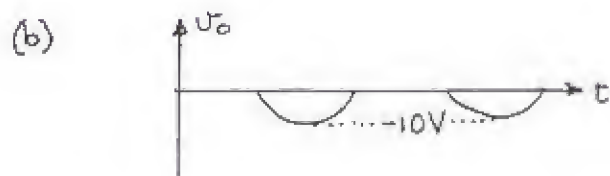
(a)



$$V_{p+} = \underline{10V} \quad V_{p-} = \underline{0V}$$

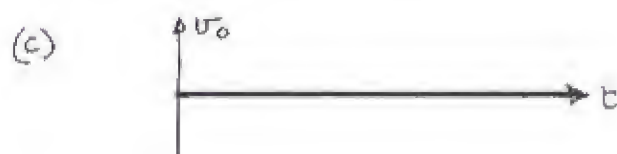
$$f = \underline{1kHz}$$

CHAPTER 3 PROBLEMS



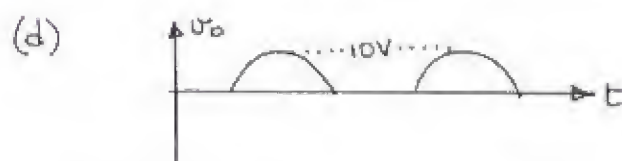
$$V_{p+} = \underline{0V} \quad V_{p-} = \underline{-10V}$$

$$f = 1\text{kHz}$$



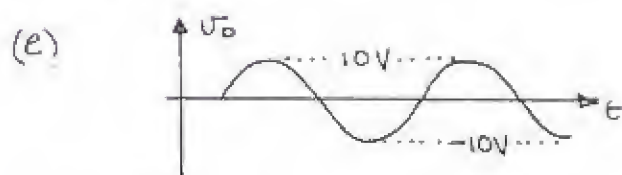
$$V_o = \underline{0V}$$

Neither D_1 nor D_2 conducts so there is no output.



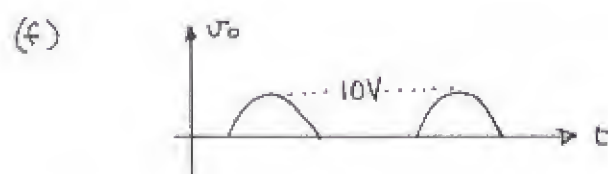
$$V_{p+} = \underline{10V} \quad V_{p-} = \underline{0V} \quad f = 1\text{kHz}$$

Both D_1 and D_2 conduct when $V_i > 0$



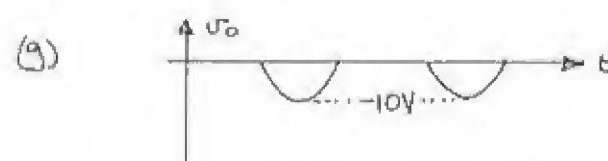
$$V_{p+} = \underline{10V} \quad V_{p-} = \underline{-10V} \quad f = 1\text{kHz}$$

D_1 conducts when $V_i > 0$ and D_2 conducts when $V_i < 0$. Thus the output follows the input.



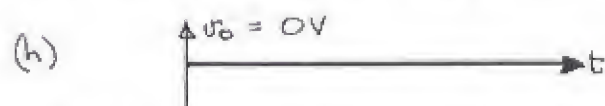
$$V_{p+} = \underline{10V} \quad V_{p-} = \underline{0V} \quad f = 1\text{kHz}$$

D_1 is cutoff when $V_i < 0$

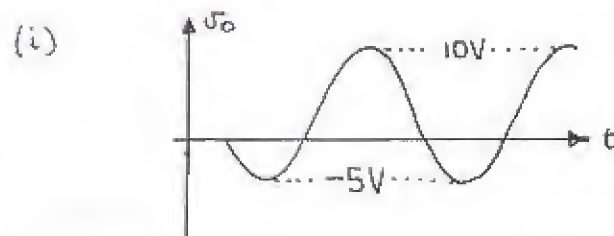


$$V_{p+} = \underline{0V} \quad V_{p-} = \underline{-10V} \quad f = 1\text{kHz}$$

D_1 shorts to ground when $V_i > 0$ and is cut off when $V_i < 0$ whereby the output follows V_i .



$V_o = \underline{0V}$ ~ The output is always shorted to ground as D_1 conducts when $V_i > 0$ and D_2 conducts when $V_i < 0$.



$$V_{p+} = \underline{10V} \quad V_{p-} = \underline{-5V} \quad f = 1\text{kHz}$$

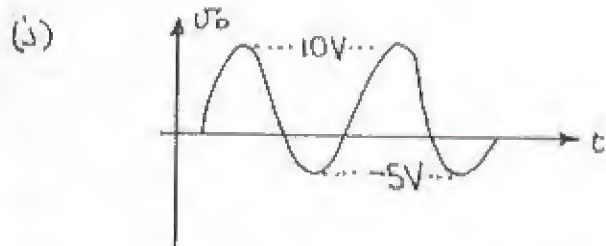
When $V_i > 0$, D_1 is cutoff and V_o follows V_i .

CHAPTER 3 PROBLEMS

3.5

-When $V_I < 0$, D_1 is conducting and the circuit becomes a voltage divider where the negative peak is

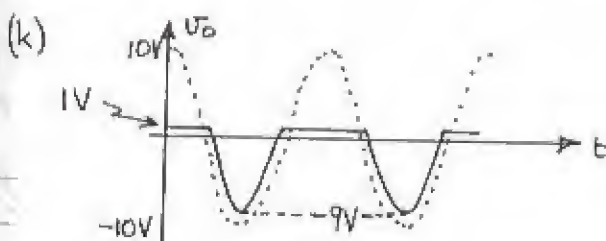
$$\frac{1k\Omega}{1k\Omega + 1k\Omega} \cdot -10V = -5V$$



$$V_{p+} = 10V \quad V_{p-} = -5V \quad f = 1kHz$$

-When $V_I > 0$, the output follows the input as D_1 is conducting.

-When $V_I < 0$, D_1 is cut off and the circuit becomes a voltage divider.

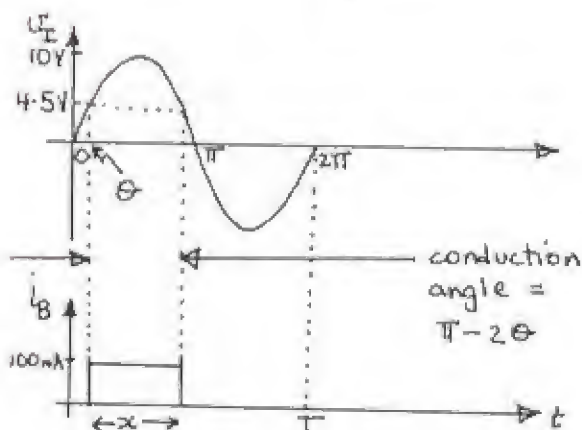
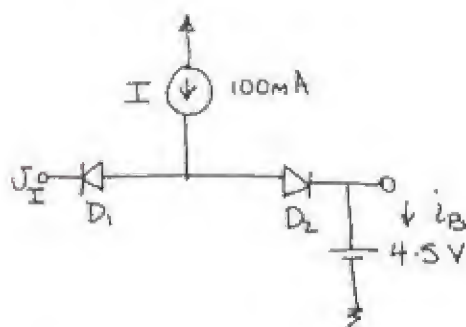


$$V_{p+} = 1V \quad V_{p-} = -9V \quad f = 1kHz$$

-When $V_I > 0$, D_1 is cut off and D_2 is conducting. The output becomes 1V.

-When $V_I < 0$, D_1 is conducting and D_2 is cut off. The output becomes:-

$$V_O = V_I + 1V$$



-When $V_I < 4.5V$ D_1 conducts and D_2 is cut off so $i_B = 0A$. For $V_I > 4.5V$ D_2 conducts and D_1 is cut off thus disconnecting the input V_I . All of the current then flows through the battery.

$$10 \sin \theta = 4.5V$$

$$\theta = \sin^{-1}(4.5/10)$$

$$\text{conduction angle} = \pi - 2\theta$$

Fraction of cycle that $i_B = 100mA$ is given by:-

$$x = \frac{\pi - 2\theta}{2\pi} = 0.35$$

$$\begin{aligned}
 i_{B \text{ avg}} &= \frac{1}{T} \int i_B dt \\
 &= \frac{1}{T} [100 \cdot 0.35T] \\
 &= \underline{\underline{35 \text{ mA}}}
 \end{aligned}$$

If V_x is reduced by 10% the peak value of i_B remains the same

$$i_{B \text{ peak}} = \underline{\underline{100 \text{ mA}}}$$

but the fraction of the cycle for conduction changes

$$\begin{aligned}
 x &= \frac{\pi - 2\theta}{2\pi} = \frac{\pi - 2 \sin^{-1}(4.5/9)}{2\pi} \\
 &= \frac{1}{3}
 \end{aligned}$$

Thus:

$$\begin{aligned}
 i_{B \text{ avg}} &= \frac{1}{T} [100 \cdot \frac{T}{3}] \\
 &= \underline{\underline{33.3 \text{ mA}}}
 \end{aligned}$$

3.6

A	B	x	y
0	0	0	0
0	1	0	1
1	0	0	1
1	1	1	1

$$x = \underline{\underline{AB}}$$

$$y = \underline{\underline{A+B}}$$

CHAPTER 3 PROBLEMS

- x and y are the same for $A = B$

- x and y are opposite if $A \neq B$

3.7

$$\frac{5-0}{R} \leq 0.1 \text{ mA}$$

$$R \geq 5/0.1 = \underline{\underline{50 \text{ k}\Omega}}$$

3.8

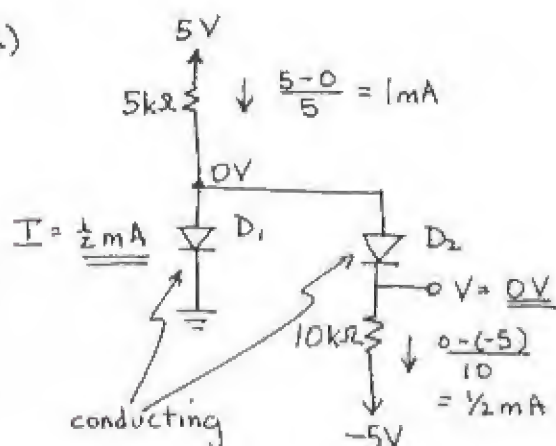
The maximum input current occurs when one input is low and the other two are high.

$$\frac{5-0}{R} \leq 0.1 \text{ mA}$$

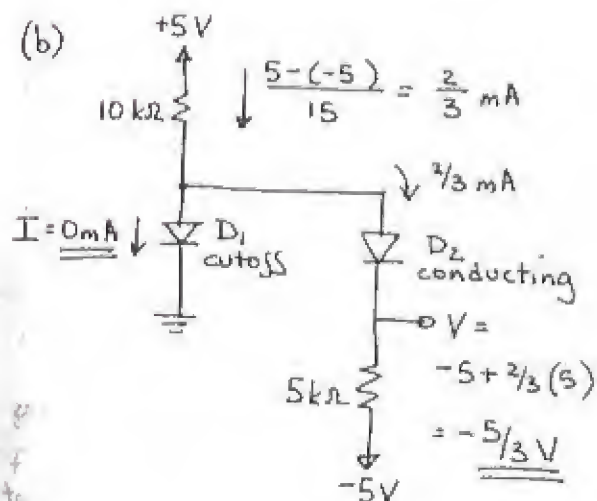
$$R \geq \underline{\underline{50 \text{ k}\Omega}}$$

3.9

(a)

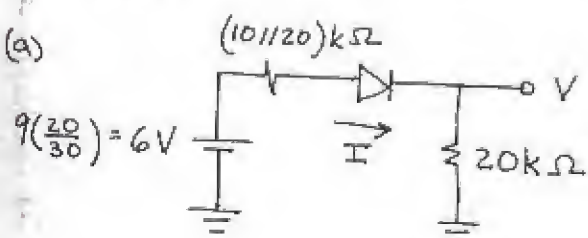


(b)



3.10

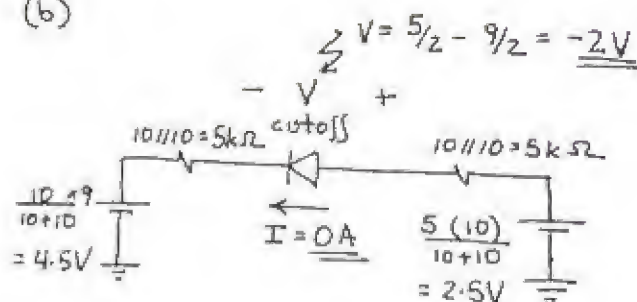
(a)



$$I = \frac{6}{(10||20) + 20} = \underline{\underline{0.225 \text{ mA}}}$$

$$V = \frac{20}{(10||20) + 20} \times 6 = \underline{\underline{4.5 \text{ V}}}$$

(b)



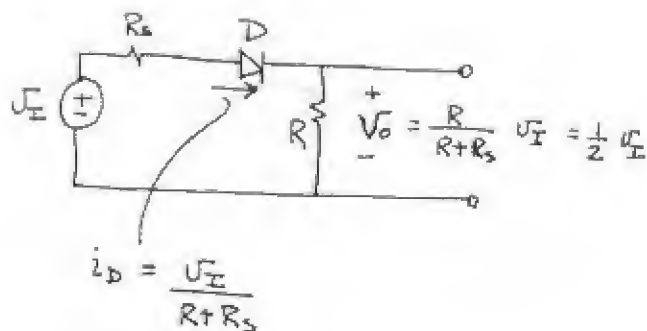
3.11

$$R \geq \frac{120\sqrt{2}}{50} \geq \underline{\underline{3.4 \text{ k}\Omega}}$$

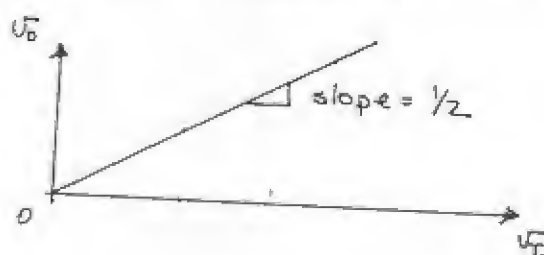
The largest reverse voltage appearing across the diode is equal to the peak input voltage

$$120\sqrt{2} = \underline{\underline{169.7 \text{ V}}}$$

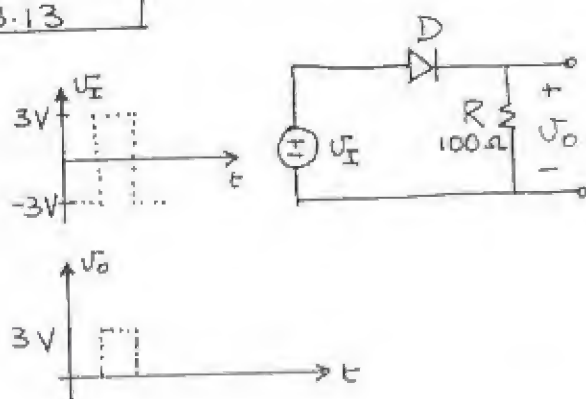
3.12



D starts to conduct when $V_I > 0$



3.13



$$V_{O, \text{peak}} = 3V$$

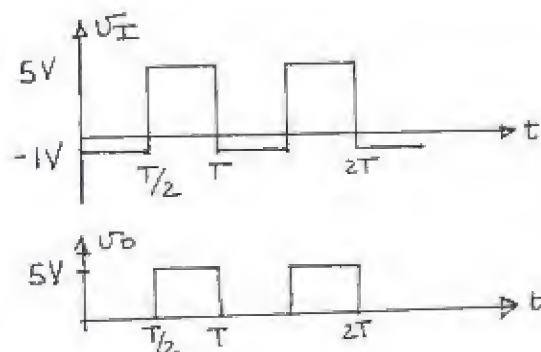
$$V_{O, \text{avg}} = \frac{1}{T} \int V_O dt = \frac{1}{T} \left[3 \frac{T}{2} \right] = \underline{\underline{3/2 V}}$$

$$i_{D, \text{peak}} = 3/100 = \underline{\underline{30 \text{ mA}}}$$

$$i_{D, \text{avg}} = \frac{3/2}{100} = \underline{\underline{15 \text{ mA}}}$$

The maximum reverse diode voltage is 3V

3.14



$$V_{O, \text{peak}} = \underline{\underline{5V}}$$

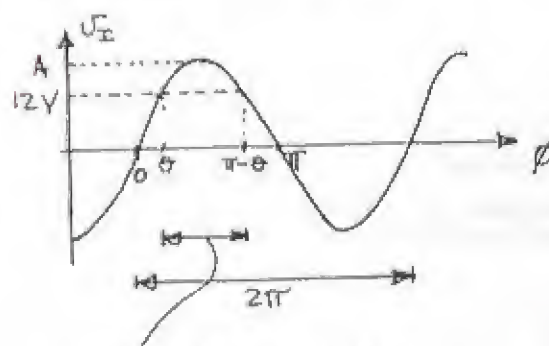
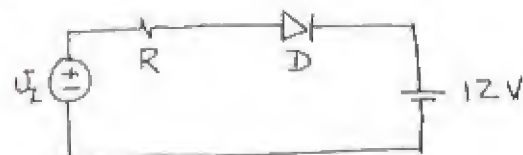
$$V_{O, \text{avg}} = \underline{\underline{2.5V}}$$

$$i_{D, \text{peak}} = \frac{V_{O, \text{peak}}}{100} = \underline{\underline{50 \text{ mA}}}$$

$$i_{D, \text{avg}} = i_{D, \text{peak}}/2 = \underline{\underline{25 \text{ mA}}}$$

maximum reverse voltage = 1V

3.15



conduction occurs

$V_I = A \sin \theta = 12$ ~ conduction across D occurs

For a conduction angle $(\pi - 2\theta)$ that is 20% of a cycle

$$\frac{\pi - 2\theta}{2\pi} = \frac{1}{5}$$

$$\theta = 0.3\pi$$

$$A = 12/\sin \theta = 14.83V$$

$$\therefore \text{Peak-to-peak sine wave voltage} = 2A = \underline{\underline{29.67V}}$$

Given the average diode current to be

$$\frac{1}{2\pi} \int_0^{2\pi} \frac{A \sin \phi - 12}{R} d\phi = 100 \text{ mA}$$

$$\frac{1}{2\pi} \left[\frac{-14.83 \cos \phi - 12 \phi}{R} \right]_{\phi=0.3\pi}^{\phi=0.7\pi} = 0.1$$

$$R = \underline{\underline{3.75 \Omega}}$$

$$\text{Peak diode current} = \frac{A-12}{R} = \underline{\underline{0.75A}}$$

$$\text{Peak reverse voltage} = A+12 = \underline{\underline{26.83V}}$$

for resistors specified to only one significant digit and peak-to-peak voltage to the nearest volt then choose $A = 15$ so the peak-to-peak sine wave voltage = 30V and $R = \underline{\underline{3 \Omega}}$

$$\begin{aligned} \text{Conduction starts at } v_z &= A \sin \theta = 12 \\ 15 \sin \theta &= 12 \\ \theta &= 0.93 \text{ rad} \end{aligned}$$

Conduction stops at $\pi - \theta$

$$\begin{aligned} \therefore \text{Fraction of cycle that current flows is } & \frac{\pi - 2\theta}{2\pi} \times 100 = 20.5 \\ & \approx \underline{\underline{20\%}} \end{aligned}$$

Average diode current =

$$\frac{1}{2\pi} \left[\frac{-15 \cos \phi - 12 \phi}{3} \right]_{\phi=0.93}^{2.21} = \underline{\underline{136 \text{ mA}}}$$

Peak diode current

$$= \frac{15-12}{3} = \underline{\underline{1A}}$$

Peak reverse voltage =

$$A + 12 = \underline{\underline{27V}}$$

3.16

V	RED	GREEN	
3V	ON	OFF	- D ₁ conducts
0	OFF	OFF	- No current flows
-3V	OFF	ON	- D ₂ conducts

3.17

$$V_T = kT/q \quad \text{where } k = 1.38 \times 10^{-23} \text{ J/K}$$

$$T = 273 + x^\circ \text{C}$$

$$q = 1.60 \times 10^{-19} \text{ C}$$

$x [^\circ \text{C}]$	$V_T [\text{mV}]$
-40	20
0	23.5
40	27
150	36.5

$$\begin{aligned} \text{for } V_T &= 25 \text{ mV} \\ T &= \underline{\underline{16.8^\circ \text{C}}} \end{aligned}$$

3.18

$$i = I_s e^{v/2 \times 0.025}$$

$$\therefore 1000 I_s = I_s e^{v/0.05}$$

$$v = \underline{\underline{0.345V}}$$

at $v = 0.7V$

$$i = I_s e^{0.7/0.05} = \underline{\underline{1.2 \times 10^6 I_s}}$$

3.19

$$i_1 = I_s e^{0.7/V_T} = 10^{-3}$$

$$i_2 = I_s e^{0.5/V_T}$$

$$\frac{i_2}{i_1} = \frac{i_2}{10^{-3}} = e^{\frac{0.5-0.7}{0.025}}$$

$$i_2 = \underline{\underline{0.335 \mu A}}$$

3.20

$$i = I_s e^{V/nV_T} = I_s e^{0.7/0.025} = 5(10^{-3})$$

$$I_s = 5(10^{-3}) e^{-0.7/0.025} = \underline{\underline{3.46 \times 10^{-45} A}}$$

V	i
0.71V	7.46 mA
0.8V	273.21 mA
0.69V	3.35 mA
0.6V	91.65 μA

$$\text{Let } i_1 = I_s e^{V_1/0.025}$$

$$i_2 = 10i_1 = I_s e^{V_2/0.025}$$

$$\frac{i_2}{i_1} = 10 = e^{\frac{V_2-V_1}{0.025}}$$

$$\therefore \Delta V = V_2 - V_1 = \underline{\underline{57.56 mV}}$$

3.21

To calculate I_s use

$$I_s = I e^{-V/nV_T} = I e^{-V/n \cdot 0.025}$$

To calculate the voltage at 1% of the measured current use

$$i_2 = 0.01 i_1 \quad \text{so,}$$

$$\frac{i_2}{i_1} = 0.01 = e^{\frac{V_2-V_1}{nV_T}}$$

$$V_2 = V_1 + nV_T \ln 0.01$$

$$= V + n(0.025) \ln(0.01)$$

V	I	$n=1$ [A]	I_s $n=2$ [A]	V $n=1$ [V]	V $n=2$ [V]
0.7	1A	6.91×10^{-13}	8.32×10^{-7}	0.585	0.470
0.650	1mA	5.11×10^{-15}	2.26×10^{-9}	0.535	0.420
0.650	10 μA	5.11×10^{-17}	2.26×10^{-11}	0.535	0.420
0.7	10mA	6.91×10^{-15}	8.32×10^{-9}	0.584	0.470

3.22

$$\text{Let } I_1 = I_s e^{V_1/nV_T} \quad \text{and}$$

$$I_2 = I_s e^{V_2/nV_T} = I_1/10$$

Calculate n by:-

$$\frac{I_2}{I_1} = e^{\frac{V_2-V_1}{nV_T}}$$

$$n = \frac{1}{V_T} \left[\frac{V_2-V_1}{\ln I_2/I_1} \right] = \frac{1}{0.025} \left[\frac{V_2-V_1}{\ln 0.1} \right]$$

Calculate I_s by:-

$$I_s = I_1 e^{-V_1/nV_T}$$

Calculate the diode voltage at 10I

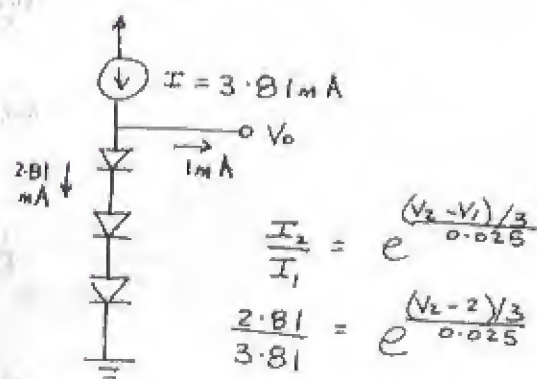
$$\text{by:- } V_3 = nV_T \ln \frac{10I_1}{I_s}$$

I	V_1 [V]	V_2 [V]	n	I_s [A]	V_3 [V]
10mA	0.7	0.6	1.737	10^{-9}	0.8
1mA	0.7	0.6	1.737	10^{-10}	0.8
10A	0.8	0.7	1.737	10^{-7}	0.9
1mA	0.7	0.58	2.085	1.47×10^{-9}	0.82
10 μ A	0.7	0.64	1.042	2.15×10^{-17}	0.7

3.23

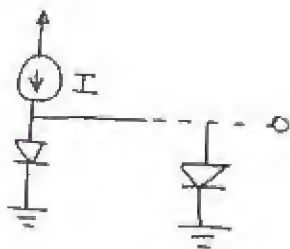
The voltage across each diode is $V_0/3$

$$I = I_s e^{\frac{V_0/3}{nV_T}} = 10^{-14} e^{\frac{3/3}{0.025}} = 3.81 \text{ mA}$$



$$\Delta V = V_2 - 2 = -22.8 \text{ mV}$$

3.24



With one diode the current

through it is

$$I = I_s e^{V_1/nV_T}$$

With two diodes in parallel, the current splits between each diode so that the diodes each has half the current

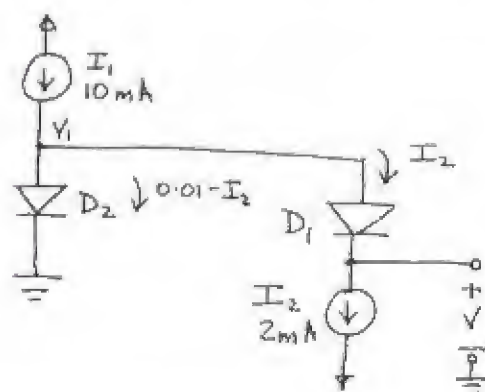
$$\frac{I}{2} = I_s e^{V_2/nV_T}$$

$$\therefore \frac{I/2}{I} = e^{\frac{V_2-V_1}{nV_T}}$$

The change in voltage is

$$\Delta V = V_2 - V_1 = nV_T \ln\left(\frac{1}{2}\right) = -17.3 \text{ mV}$$

3.25



The current through D_1 is

$$10 I_s e^{\frac{V_1-V}{nV_T}} = I_2 \quad (A)$$

The current through D_2 is

$$I_s e^{\frac{V}{nV_T}} = 0.01 - I_2$$

$$I_s = (0.01 - I_2) e^{\frac{-V}{nV_T}} \quad (B)$$

(B) \rightarrow (A)

$$10(0.01 - I_2) e^{\frac{-V}{nV_T}} = I_2$$

$$V = -V_T \ln\left(\frac{I_2}{10(0.01 - I_2)}\right)$$

$$= 0.025 \ln\left(\frac{2}{10(8)}\right) = \underline{\underline{92.2 \text{ mV}}}$$

For $V = 50 \text{ mV}$

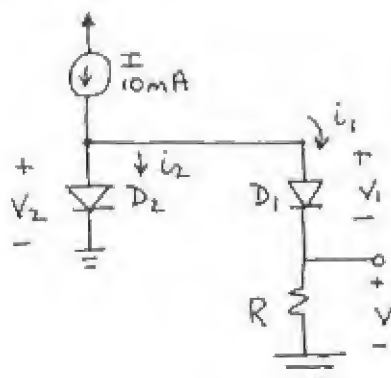
$$-V_T \ln\left(\frac{I_2}{10(10 - I_2)}\right) = 50 \times 10^{-3}$$

$$I_2 = 10(10 - I_2) e^{-2}$$

$$I_2(1 + 10e^{-2}) = 100e^{-2}$$

$$I_2 = \underline{\underline{5.75 \text{ mA}}}$$

3.26



Given for each diode $\frac{0.7}{1} \times 0.025$

$$i = I_s e^{V/V_T} \Rightarrow 10 \times 10^{-3} = I_s e^{0.7/0.025} \quad (1)$$

$$100 \times 10^{-3} = I_s e^{0.8/0.025} \quad (2)$$

②/① $10 = e^{0.1/0.025}$

$$n = 1.737$$

$$V = V_2 - V_1 = nV_T \ln(i_2/i_1) = 80 \text{ mV}$$

$$1.737 (25 \times 10^{-3}) \ln\left(\frac{0.01 - i_1}{i_1}\right) = 80$$

$$i_1 = 1.4 \text{ mA}$$

$$R = 80/i_1 = 80/1.4 = \underline{\underline{57.1 \Omega}}$$

3.27

At a constant temperature, the diode voltage drop changes with current according to

$$\Delta V = V_T \ln\left(\frac{I_2}{I_1}\right)$$

where

$$V_T = \frac{kT}{q} = \frac{1.38 \times 10^{-23} (273 + \text{Temp. } ^\circ\text{C})}{1.6 \times 10^{-19}}$$

thus:

TEMP ($^\circ\text{C}$)	0	50	75	100	-50
V_T (mV)	23.5	27.9	30	32.2	19.2

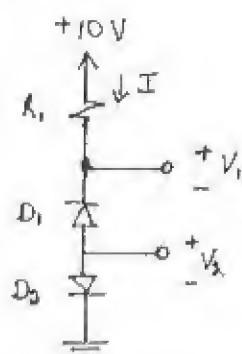
At a constant current, the diode voltage drop changes with temperature according to

$$\Delta V = -2 (\text{mV}) \times \text{TEMPERATURE CHANGE } (^\circ\text{C})$$

thus:

- (a) 620 mV at $10 \mu\text{A}$ and 0°C
 728 mV at 1 mA and 0°C
 678 mV at 1 mA and 25°C

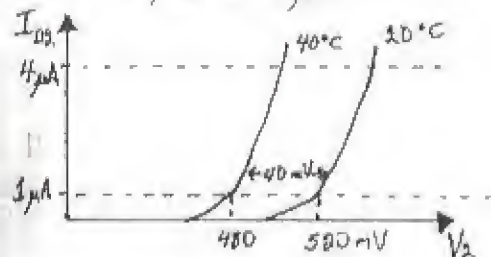
3.28

At 20°C :

$$V_{R1} = V_2 = 520 \text{ mV}$$

$$R_1 = 520 \text{ k}\Omega$$

$$I = \frac{520 \text{ mV}}{520 \text{ k}\Omega} = 1 \mu\text{A}$$

At 40°C , $I = 4 \mu\text{A}$ 

$$V_2 = 480 + 2.3 \times 1 \times 25 \log 4$$

$$= 514.6 \text{ mV}$$

$$V_{R1} = 4 \mu\text{A} \times 520 \text{ k}\Omega = \underline{2.08 \text{ V}}$$

At 0°C , $I = \frac{1}{4} \mu\text{A}$

$$V_2 = 560 - 2.3 \times \frac{1}{4} \times 25 \log 4$$

$$= \underline{525.4 \text{ mV}}$$

$$V_{R1} = \frac{1}{4} \times 520 = \underline{0.13 \text{ V}}$$

3.29

The voltage drop $= 700 - 580 = 120 \text{ mV}$

Since the diode voltage decreases by approximately 2 mV for every 1°C increase in temperature, the junction temperature must have increased by

$$\frac{120}{2} = \underline{60^\circ\text{C}}$$

Power being dissipated =

$$580 \times 10^{-3} \times 15 = \underline{8.7 \text{ W}}$$

Thermal Resistance = temperature rise / watt

$$= 60 / 8.7 = \underline{6.9^\circ\text{C/W}}$$

3.30

$$i = I_s e^{V/nV_T}$$

$$10 = I_s e^{0.8/2(0.025)}$$

$$I_s = 1.12 \times 10^{-6} \text{ A}$$

For current varying between $i_1 = 0.5 \text{ mA}$ to $i_2 = 1.5 \text{ mA}$, the voltage varies from

$$V_1 = 2(0.025) \ln \left(\frac{0.5 \times 10^{-3}}{1.12 \times 10^{-6}} \right) = \underline{0.305 \text{ V}}$$

to:

$$V_2 = 2(0.025) \ln \left(\frac{1.5 \times 10^{-3}}{1.12 \times 10^{-6}} \right) = \underline{0.360 \text{ V}}$$

∴

the voltage decreases by approximately 2 mV for every 1°C increase in temperature, the voltage may vary by $\pm 50 \text{ mV}$ for the $\pm 25^\circ\text{C}$ temperature variation.

3.31

$$i = I_s e^{v/nV_T}$$

$$\frac{I_{s2}}{I_{s1}} = \frac{1}{0.1 \times 10^{-3}} = 10^4$$

For identical currents

$$I_{s1} e^{v_1/nV_T} = I_{s2} e^{v_2/nV_T}$$

$$e^{\frac{v_1 - v_2}{nV_T}} = 10^4$$

$$v_1 - v_2 = nV_T \ln 10^4$$

$$= 26 \times 10^{-3} \ln 10^4$$

$$= +0.23V$$

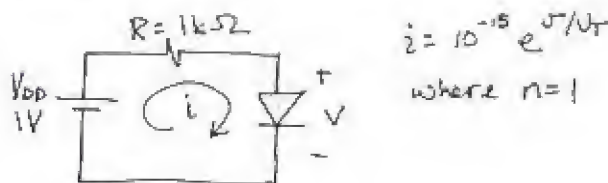
I.E. THE VOLTAGE DIFFERENCE BETWEEN THE TWO DIODES IS +0.23V INDEPENDENT OF THE CURRENT.

HOWEVER, SINCE THE TWO CURRENTS CAN VARY BY A FACTOR OF 3 (0.5 mA TO 1.5 mA) THE DIFFERENCE VOLTAGE WILL BE:

$$0.23V \pm nV_T \ln 3 = 0.23V \pm 2.75 mV$$

SINCE TEMPERATURE CHANGE AFFECTS BOTH DIODES SIMILARLY THE DIFFERENCE VOLTAGE REMAINS CONSTANT.

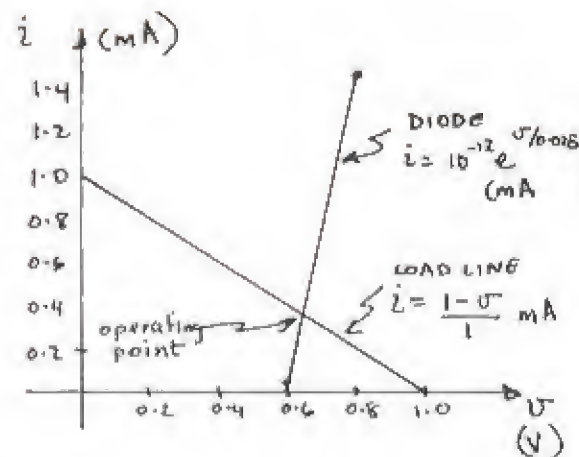
3.32



$$v = 0.7V \quad i = 1.45 mA$$

$$v = 0.6V \quad i = 0.026 mA$$

A sketch of the graphical construction to determine the operating point is shown below.



From the above sketch we see that the operating point must lie between $v = 0.6$ and $0.7V$ and $i = 0.3$ to $0.4 mA$. To find the point more accurately an enlarged graph is plotted.

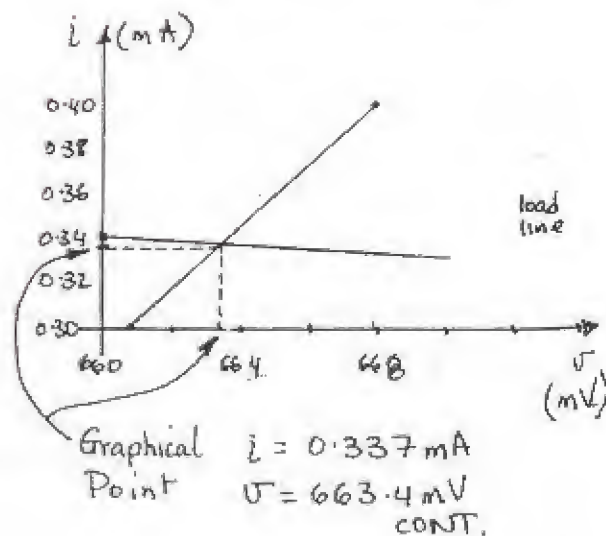
$$\text{For } i = 0.3 mA = 10^{-12} e^{v/0.026} \Rightarrow v = 660.7 mV$$

$$\text{For } i = 0.4 mA = 10^{-12} e^{v/0.026} \Rightarrow v = 667.9 mV$$

For the load line:

$$v = 660 mV \Rightarrow i = 0.34 mA$$

$$v = 670 mV \Rightarrow i = 0.33 mA$$



Comparing the graphical results to the exponential model gives:

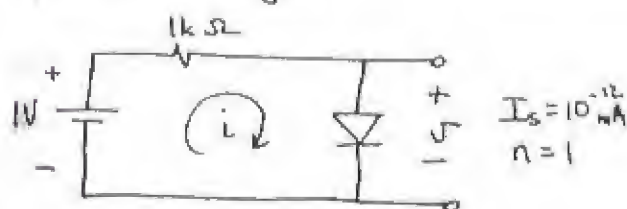
$$\text{At } i = 0.337 \text{ mA} = 10^{-12} e^{v/0.025}$$

$$\Rightarrow v = 663.6 \text{ mV}$$

which is only $(663.6 - 663.4) = 0.2 \text{ mV}$ greater than the value found graphically!

3.33

Iterative Analysis:



$$\#1 \quad v = 0.7 \text{ V} \quad i = \frac{1 - 0.7}{1} = 0.3 \text{ mA}$$

$$\#2 \quad v = 0.25 \ln\left(\frac{0.3}{10^{-12}}\right) = 0.6607 \text{ V}$$

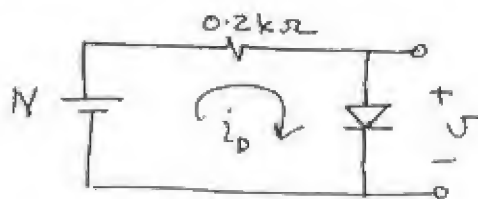
$$i = \frac{1 - 0.6607}{1} = 0.3393 \text{ mA}$$

$$\#3 \quad v = 0.25 \ln\left(\frac{0.3393}{10^{-12}}\right) = 0.6638 \text{ V}$$

$$i = \frac{1 - 0.6638}{1} = 0.3362$$

∞ i did not change by much stop here.

3.34



$$(a) \quad i_D = \frac{1 - 0.7}{0.2} = 1.5 \text{ mA}$$

(b) Iterative Analysis given $v_D = 0.7 \text{ V}$ at $i_D = 1 \text{ mA}$

$$\#1 \quad v = 0.7 \text{ V} \quad i_D = \frac{1 - 0.7}{0.2} = 1.5 \text{ mA}$$

$$\#2 \quad i = I_s e^{v/nV_T} \quad n=2$$

$$\frac{i_2}{i_1} = e^{\frac{v_2 - v_1}{0.05}}$$

$$\text{thus } v_2 = v_1 + 0.05 \ln i_2/i_1$$

$$\text{so for } i = 1.5 \text{ mA}$$

$$v = 0.7 + 0.05 \ln \frac{1.5}{1} \quad i_D = \frac{1 - 0.720}{0.2} = 1.4 \text{ mA}$$

#3

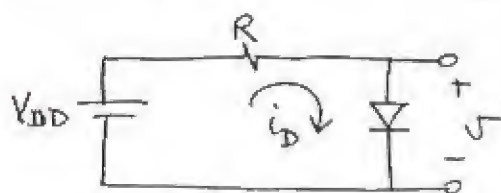
$$v = 0.720 + 0.05 \ln \left(\frac{1.4}{1.5}\right) \quad i_D = \frac{1 - 0.716}{0.2} = 1.42 \text{ mA}$$

#4

$$v = 0.716 + 0.05 \ln \left(\frac{1.42}{1.4}\right) \quad i_D = 1.42 \text{ mA}$$

$$= 0.716 \text{ V}$$

3.35



Derivation of iterative equation

$$i_D = I_s e^{V/V_T}$$

$$\frac{i_{D2}}{i_{D1}} = e^{\frac{V_2 - V_1}{n V_T}}$$

$$V_2 = V_1 + n V_T \ln\left(\frac{i_{D2}}{i_{D1}}\right)$$

$$= V_1 + \Delta V \log\left(\frac{i_{D2}}{i_{D1}}\right)$$

(a) $V = 0.7 \text{ V}$ $i_D = \frac{10 - 0.7}{9.3} = 1 \text{ mA}$

(b) $V = 0.7 \text{ V}$ $i_D = \frac{3 - 0.7}{2.3} = 1 \text{ mA}$

~ for both these cases the diode is rated at 1mA for 0.7V so stop.

(c) $V_{DD} = 2 \text{ V}$ $R = 2 \text{ k}\Omega$

#1 $V = 0.7 \text{ V}$ $i_D = \frac{2 - 0.7}{2} = 0.65 \text{ mA}$

#2 $V = 0.7 + 0.1 \log\left(\frac{0.650}{10}\right) = 0.581 \text{ V}$

$$i_D = \frac{2 - 0.581}{2} = 0.709 \text{ mA}$$

#3 $V = 0.581 + 0.1 \log\left(\frac{0.709}{0.650}\right)$

$$= 0.584 \text{ V}$$

$$i_D = \frac{2 - 0.584}{2} = 0.708 \text{ mA}$$

(d) $V_{DD} = 2 \text{ V}$ $R = 2 \text{ k}\Omega$

#1 $V = 0.7 \text{ V}$ $i_D = \frac{2 - 0.7}{2}$

$$= 0.650 \text{ mA}$$

#2.

$$V = 0.7 + 0.1 \log\left(\frac{0.650}{1}\right) \quad i_D = \frac{2 - 0.681}{2}$$

$$= 0.681 \text{ V} \quad = 0.659 \text{ mA}$$

#3

$$V = 0.681 + 0.1 \log\left(\frac{0.659}{0.650}\right) \quad i_D = \frac{2 - 0.682}{2}$$

$$= 0.682 \text{ V} \quad = 0.659 \text{ mA}$$

(e) $V_{DD} = 1 \text{ V}$ $R = 0.3 \text{ k}\Omega$

#1 $V = 0.7 \text{ V}$ $i_D = \frac{1 - 0.7}{0.3} = 1 \text{ mA}$

#2

$$V = 0.7 + 0.1 \log\left(\frac{1}{10}\right) \quad i_D = \frac{1 - 0.6}{0.3} = 1.333 \text{ mA}$$

$$= 0.6 \text{ V}$$

#3

$$V = 0.6 + 0.1 \log\left(\frac{1.333}{1}\right) \quad i_D = \frac{1 - 0.612}{0.3} = 1.293 \text{ mA}$$

$$= 0.612 \text{ V}$$

#4

$$V = 0.612 + 0.1 \log\left(\frac{1.293}{1.333}\right) \quad i_D = \frac{1 - 0.611}{0.3} = 1.297 \text{ mA}$$

$$= 0.611 \text{ V}$$

#5

$$V = 0.611 + 0.1 \log\left(\frac{1.297}{1.293}\right) \quad i_D = 1.297 \text{ mA}$$

$$= 0.611 \text{ V}$$

(f) $V_{DD} = 1 \text{ V}$ $R = 0.3 \text{ k}\Omega$

#1 $V = 0.7 \text{ V}$ $i_D = \frac{1 - 0.7}{0.3} = 1 \text{ mA}$

CONST.

#2

$$V = 0.7 + 0.06 \log \frac{1}{10} \quad i_D = \frac{1 - 0.640}{0.3}$$

$$= 0.640 \text{ V} \quad = 1.2 \text{ mA}$$

#3

$$V = 0.645 + 0.06 \log \frac{1.2}{1} \quad i_D = \frac{1 - 0.645}{0.3}$$

$$= 0.645 \text{ V} \quad = 1.183 \text{ mA}$$

#4

$$V = 0.645 + 0.06 \log \frac{1.183}{1.2}$$

$$= 0.645 \text{ V} \quad i_D = 1.183 \text{ mA}$$

(9) $V_{DD} = 1\text{V} \quad R = 0.3 \text{ k}\Omega$

#1 $V = 0.7 \quad i_D = \frac{1 - 0.7}{0.3} = 1 \text{ mA}$

#2

$$V = 0.7 + 0.12 \log \frac{1}{10} \quad i_D = \frac{1 - 0.580}{0.3}$$

$$= 0.580 \text{ V} \quad = 1.381 \text{ mA}$$

#3

$$V = 0.580 + 0.12 \log \frac{1.381}{1} \quad i_D = \frac{1 - 0.597}{0.3}$$

$$= 0.597 \text{ V} \quad = 1.343 \text{ mA}$$

#4

$$V = 0.597 + 0.12 \log \frac{1.343}{1.381} \quad i_D = \frac{1 - 0.596}{0.3}$$

$$= 0.596 \text{ V} \quad = 1.347 \text{ mA}$$

#5

$$V = 0.596 + 0.12 \log \frac{1.347}{1.343}$$

$$= 0.596 \text{ V} \quad i_D = 1.347 \text{ mA}$$

(h) $V_{DD} = 0.5 \text{ V} \quad R = 30 \text{ k}\Omega$

#1 let $V = 0.4 \text{ V} \quad i_D = \frac{0.5 - 0.4}{30}$

$$= 3.333 \mu\text{A}$$

#2

$$V = 0.7 + 0.1 \log \frac{3.333 \times 10^{-3}}{10} \quad i_D = \frac{0.5 - 0.352}{30}$$

$$= 0.352 \text{ V} \quad = 4.933 \mu\text{A}$$

#3

$$V = 0.352 + 0.1 \log \frac{4.933}{3.333} \quad i_D = \frac{0.5 - 0.369}{30}$$

$$= 0.369 \text{ V} \quad = 4.367 \mu\text{A}$$

#4

$$V = 0.369 + 0.1 \log \frac{4.367}{4.933} \quad i_D = \frac{0.5 - 0.364}{30}$$

$$= 0.364 \text{ V} \quad = 4.533 \mu\text{A}$$

#5

$$V = 0.364 + 0.1 \log \left(\frac{4.533}{4.367} \right) \quad i_D = \frac{0.5 - 0.366}{30}$$

$$= 0.366 \text{ V} \quad = 4.467 \mu\text{A}$$

#6

$$V = 0.366 + 0.1 \log \frac{4.467}{4.533} \quad i_D = \frac{0.5 - 0.365}{30}$$

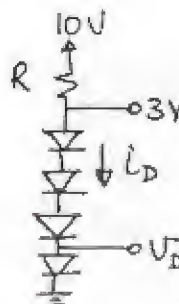
$$= 0.365 \text{ V} \quad = 4.5 \mu\text{A}$$

#7

$$V = 0.365 + 0.1 \log \frac{4.5}{4.467}$$

$$= 0.365 \text{ V} \quad i_D = 4.5 \mu\text{A}$$

3.36



$$V_D = \frac{3}{4} = 0.75 \text{ V}$$

$$i_D = I_s e^{V_D / nV_T}$$

$$\frac{i_{D2}}{i_{D1}} = e^{\frac{V_{D2} - V_{D1}}{nV_T}}$$

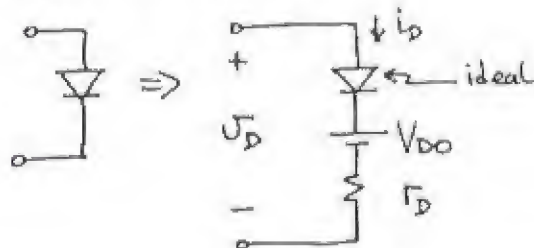
CONST.

$$\begin{aligned} \therefore i_D = i_{D2} = i_{D1} e^{\frac{V_{D2} - V_{D1}}{nV_T}} \\ = 1 \times e^{\frac{0.75 - 0.7}{1 \times 0.025}} \\ = 7.389 \text{ mA} \end{aligned}$$

$$\therefore R = \frac{10 - 3}{i_D} = \frac{10 - 3}{7.389} = \underline{\underline{0.947 \text{ k}\Omega}}$$

3.37

Piecewise linear model:



Given $n=2$, $V_D=0.7\text{V}$ $i_D=1\text{mA}$

The current through the diode is given by:

$$i_D = \frac{V_D - V_{D0}}{r_D} \quad \sim \text{need to find the parameters } V_{D0} \text{ and } r_D$$

Using the exponential model to find the diode voltage at 10mA

$$\frac{i_{D2}}{i_{D1}} = e^{\frac{V_{D2} - V_{D1}}{nV_T}}$$

$$\begin{aligned} V_{D2} &= nV_T \ln\left(\frac{i_{D2}}{i_{D1}}\right) = 0.05 \ln\left(\frac{10}{1}\right) \\ &= 0.815 \text{ V} \end{aligned}$$

FINDING V_{D0} & r_D using the given facts:

$$i_D = \frac{0.7 - V_{D0}}{r_D} = 1 \text{ mA} \quad (1)$$

$$i_D = \frac{0.815 - V_{D0}}{r_D} = 10 \text{ mA} \quad (2)$$

$$\frac{(2)}{(1)} \Rightarrow \frac{0.815 - V_{D0}}{0.7 - V_{D0}} = 10$$

$$V_{D0} = \underline{\underline{0.687 \text{ V}}}$$

$$r_D = \frac{0.7 - V_{D0}}{1} = \underline{\underline{12.8 \Omega}}$$

Using the piecewise linear model

$$i_D = \frac{V_D - 0.687}{12.8} \Rightarrow V_D = 0.687 + 12.8 i_D$$

Using the exponential model

$$\frac{i_{D2}}{i_{D1}} = e^{\frac{V_{D2} - 0.7}{0.05}} \Rightarrow V_D = 0.7 + 0.05 \ln\left(\frac{i_{D2}}{1}\right)$$

i_D (mA)	PIECEWISE LINEAR V_D (V)	EXPONENTIAL V_D (V)	Error (mV)
0.5	0.693	0.655	28
5	0.751	0.780	-29.5
14	0.866	0.832	34

3.38

Looking at the copy of Fig 3.12 below, we see at

$$i_D = 1 \text{ mA} \rightarrow V_D = 0.7 \text{ V}$$

$$i_D = 10 \text{ mA} \rightarrow V_D = 0.8 \text{ V}$$

$$\therefore \text{slope} = \frac{1}{r_D} = \frac{10 - 1}{0.8 - 0.7} = 90 \frac{\text{mA}}{\text{V}}$$

$$\therefore r_D = \frac{1}{90 \times 10^{-3}} = \underline{\underline{11.15 \Omega}}$$

To find V_{D0} :

$$I_D = \frac{V_D - V_{D0}}{r_D}$$

$$10^{-3} = \frac{0.7 - V_{D0}}{11.1} \Rightarrow V_{D0} = \underline{\underline{0.689V}}$$

(a) The load line intersects the exponential model at:

$$V_D = \underline{\underline{0.73V}} \quad I_D = \underline{\underline{1.7mA}}$$

(b) The load line intersects the straight-line model at

$$V_D = \underline{\underline{0.7V}} \quad I_D = \underline{\underline{2mA}}$$

3.40

Calculating the parameters r_D & V_{D0} for the battery plus resistor model

$$I_D = I_S e^{V_D / nV_T} \quad n=1$$

$$\text{For } I_D = 0.1 I_D$$

$$V_{D2} = 0.7 + 0.025 \ln(0.1) = \underline{\underline{0.642V}}$$

$$\text{For } I_D = 10 I_D$$

$$V_{D3} = 0.7 + 0.025 \ln(10) = \underline{\underline{0.758V}}$$

Note that since the specifications for all of the diodes are given for 0.7V, the end voltages are the same as the voltage change for relative currents are independent to I_D & I_S .

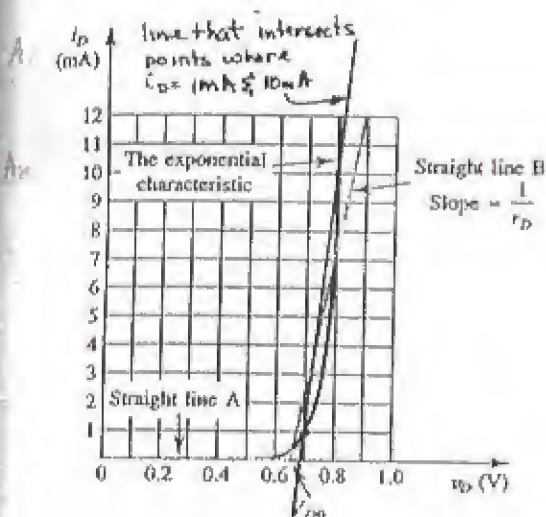
$$\circ \circ \quad V_{D2} = V_{D0} + I_{D2} r_D \quad (1)$$

$$V_{D3} = V_{D0} + I_{D3} r_D \quad (2)$$

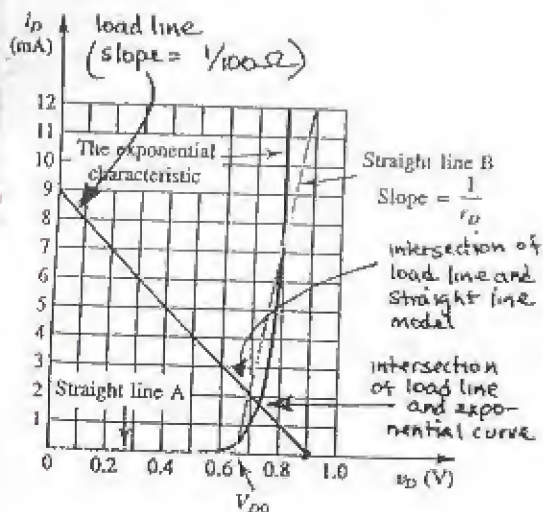
$$(2) \rightarrow (1)$$

$$V_{D3} - V_{D2} = (I_{D3} - I_{D2}) r_D$$

CONST.



3.39



$$0.758 - 0.642 = (0.1 I_D - 0.1 I_D) r_D$$

$$0.166 = 9.9 I_D r_D$$

$$r_D = \frac{0.0117}{I_D} \quad (3)$$

$$\text{For (a) } I_D = 1 \text{ mA} \quad r_D = \frac{0.0117}{1} = \underline{\underline{11.75 \Omega}}$$

$$(b) I_D = 1 \text{ A} \quad r_D = \frac{0.0117}{1} = \underline{\underline{0.0117 \Omega}}$$

$$(c) I_D = 10 \mu\text{A} \quad r_D = \frac{0.0117}{10 \mu\text{A}} = \underline{\underline{1.17 \text{ k}\Omega}}$$

$$(3) \rightarrow (1)$$

$$0.642 = V_{D0} + 0.1 I_D \times \frac{0.0117}{I_D}$$

$$= V_{D0} + 0.00117$$

$$V_{D0} = \underline{\underline{0.641 \text{ V}}} \leftarrow \text{same for all diodes}$$

3.41

Since for a current of 10 mA, the diode voltage is 0.8 V, this would be a suitable choice for the constant-voltage-drop model.

3.42

Constant Voltage drop Model:

$$\text{Using } V_D = 0.7 \text{ V} \Rightarrow I_{D1} = \frac{V - 0.7}{R}$$

$$\text{Using } V_D = 0.6 \text{ V} \Rightarrow I_{D2} = \frac{V - 0.6}{R}$$

For the difference in currents to vary by only 1% \Rightarrow

$$I_{D2} = 1.01 I_{D1}$$

$$V - 0.6 = 1.01 (V - 0.7)$$

$$V = \underline{\underline{1.0 \text{ V}}}$$

$$\text{For } V = 2 \text{ V} \quad R = 1 \text{ k}\Omega$$

$$\text{At } V_D = 0.7 \text{ V} \quad I_{D1} = \frac{2 - 0.7}{1} = 1.3 \text{ mA}$$

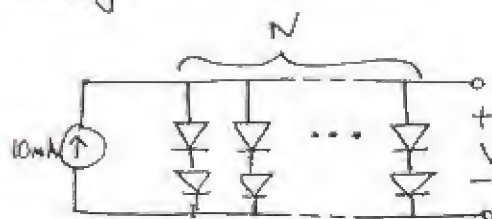
$$V_D = 0.6 \text{ V} \quad I_{D2} = \frac{2 - 0.6}{1} = 1.4 \text{ mA}$$

$$\frac{I_{D2}}{I_{D1}} = \frac{1.4}{1.3} = 1.08$$

Thus the percentage difference is 8%

3.43

Since $2 V_D = 1.4 \text{ V}$ is close to the required 1.25 V , use N parallel pairs of diodes to split the current evenly.



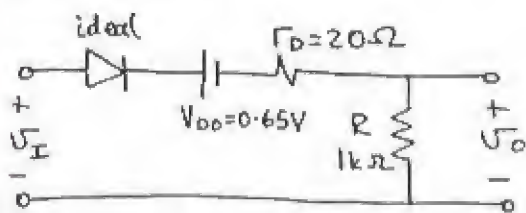
$$V = 2 \left[0.7 + 0.1 \log \frac{10/N}{20} \right] = 1.25 \text{ V}$$

$$N = 2.8 \Rightarrow \text{Use } \underline{\underline{3 \text{ sets of diodes}}}$$

$$V = 2 \left(0.7 + 0.1 \log \frac{10/3}{20} \right) = \underline{\underline{1.244 \text{ V}}}$$

3.44

Piecewise linear model in a half-wave rectifier.

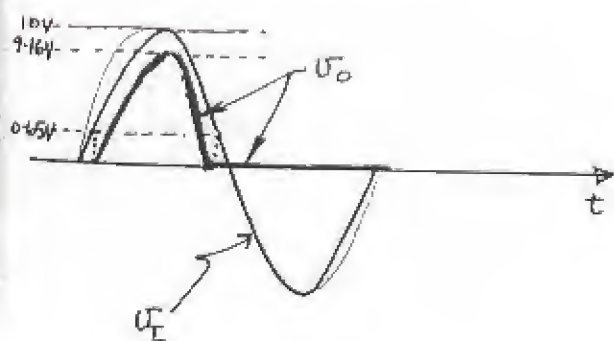
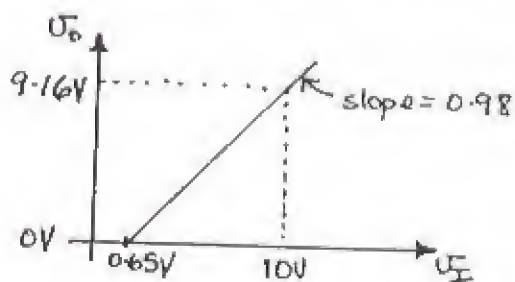


$$U_O = \frac{U_I - V_{D0}}{R_D + R} R, \text{ for } U_I \gg V_{D0}$$

Thus, $U_O = 0.98(U_I - 0.65)$ for $U_I \gg 0.65$

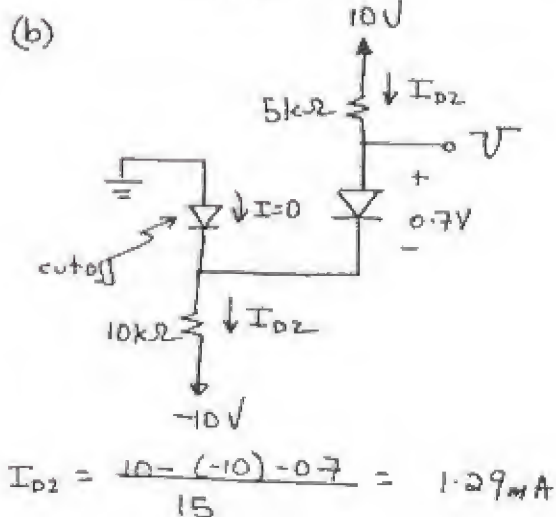
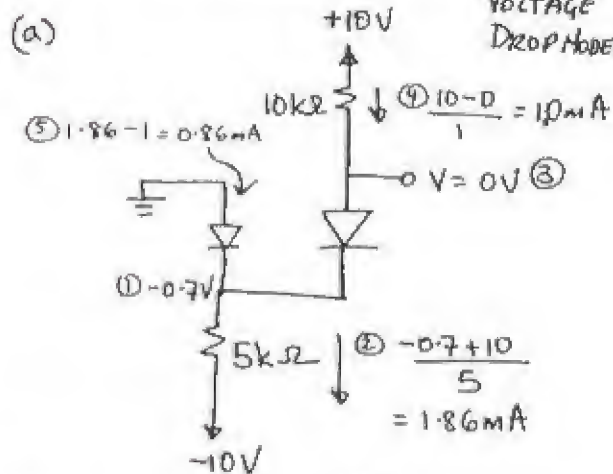
$$U_O = 0 \text{ for } U_I < 0.65V$$

Sketch of transfer characteristic:

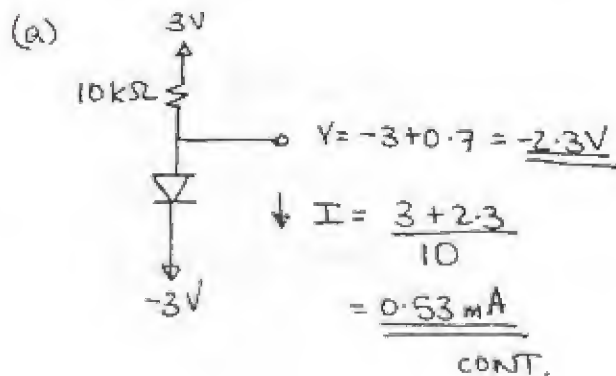


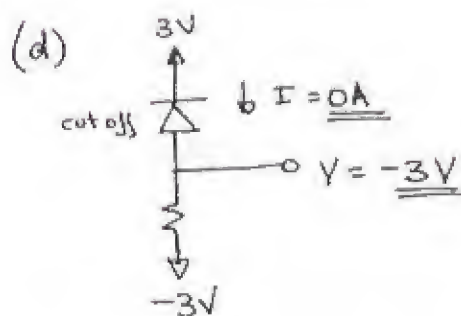
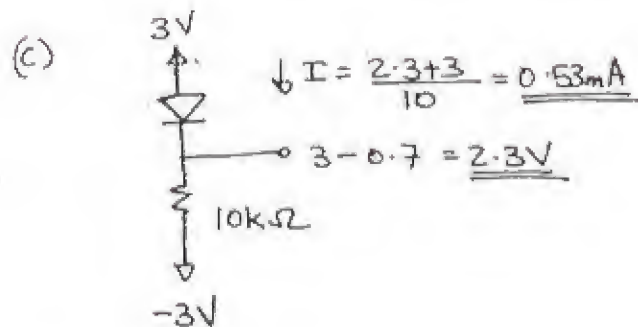
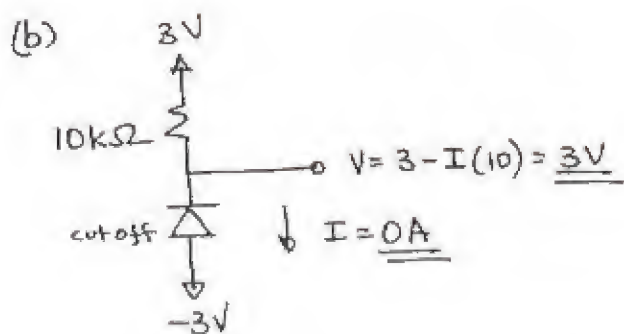
3.45

Refer to example 3-2 ~ CONSTANT VOLTAGE DROP MODEL

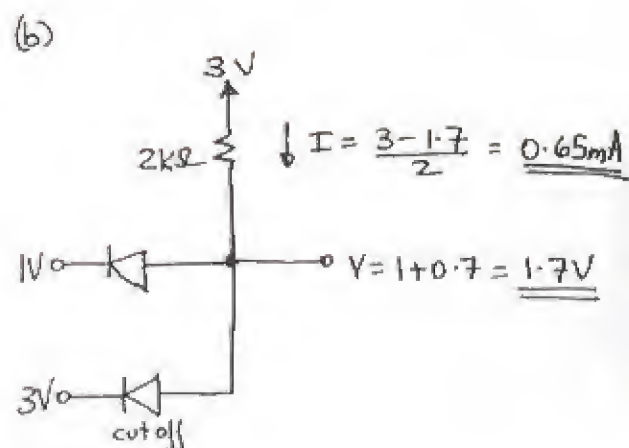
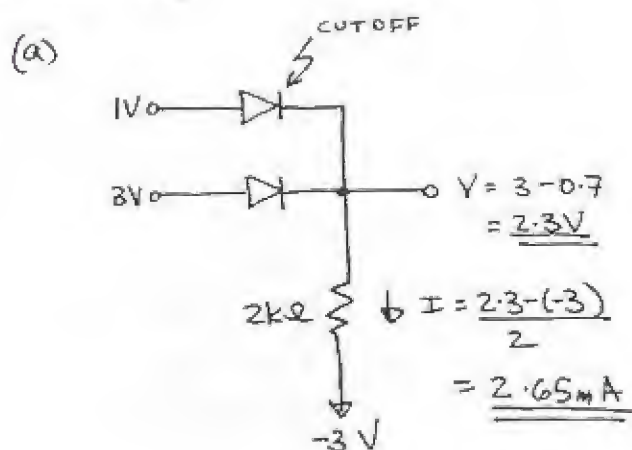


3.46

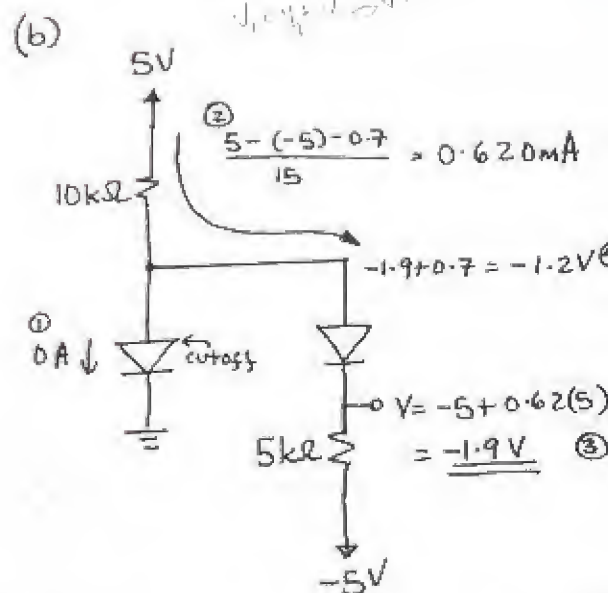
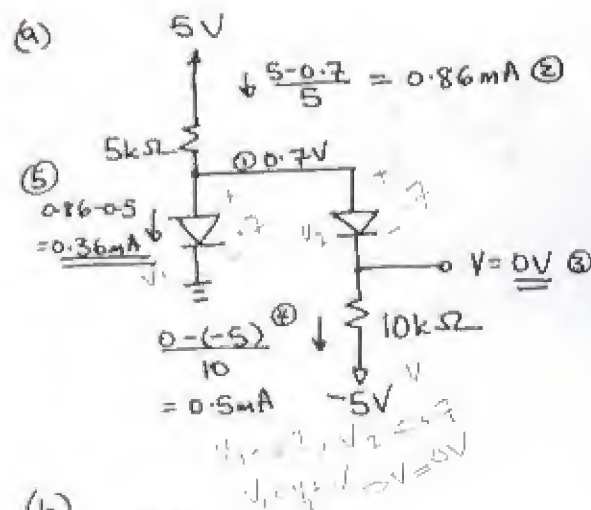




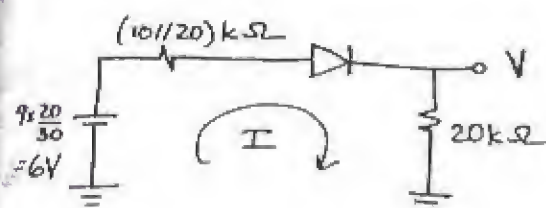
3.47



3.48

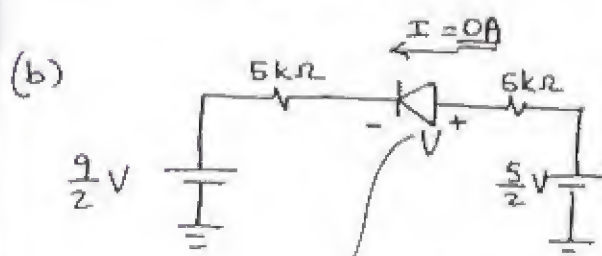


3.49



$$I = \frac{6 - 0.7}{(10||20) + 20} = \underline{0.199 \text{ mA}}$$

$$V = 20I = \underline{3.98 \text{ V}}$$

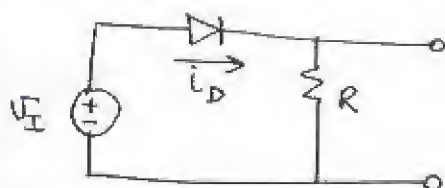


cutoff $\therefore \frac{5}{2} < \frac{9}{2}$

$$\therefore I = \underline{0 \text{ A}}$$

$$V = \frac{9}{2} - \frac{5}{2} = \underline{-2 \text{ V}}$$

3.50



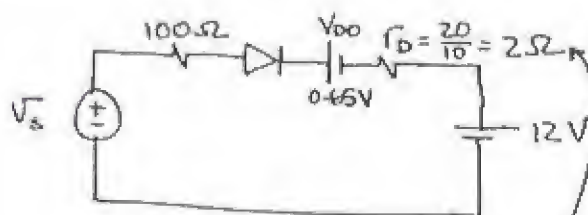
$$i_{D, \text{peak}} = \frac{V_{I, \text{peak}} - 0.7}{R} \ll 50$$

$$R \gg \frac{120\sqrt{2} - 0.7}{50} = \underline{3.38 \text{ k}\Omega}$$

Reverse voltage = $120\sqrt{2} = 169.7 \text{ V}$.
The design is essentially the same
since the supply voltage $\gg 0.7 \text{ V}$

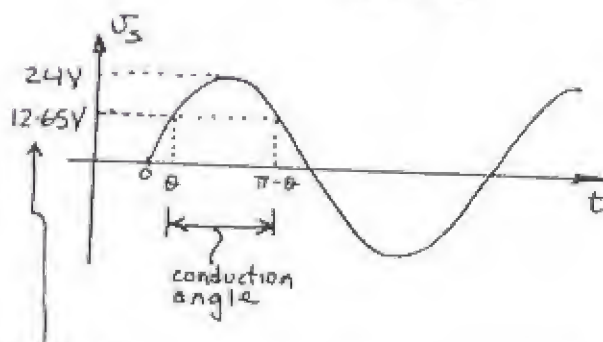
3.51

Battery plus resistance model



since the diode has 10x the area r_D is $1/10$ as big.

$$i_D = I_s e^{V/nkT} = \frac{V_s - V_{D0} - 12}{100 + 2}$$



Conduction starts when $V_s > 12 + V_{D0}$
 $V_s > 12.65 \text{ V}$

$$\therefore 24 \sin \theta = 12.65^\circ$$

$$\theta = 0.555 \text{ rad}$$

$$\text{Conduction angle} = \pi - 2\theta$$

$$= 2.031 \text{ rad.}$$

$$\text{Fraction of cycle for conduction} = \frac{2.031}{2\pi} = \underline{0.323}$$

CONST.

$$i_{D, \text{peak}} = \frac{24 - 12.68}{100 + 2} = \underline{\underline{0.111 \text{ A}}}$$

Maximum reverse voltage occurs across the diode when V_s is at its negative peak and is equal to:

$$24 + 12 = \underline{\underline{36 \text{ V}}}$$

3.52

Using the exponential model

$$i_D = I_s e^{DV/nV_T}$$

FOR A +10mV CHANGE

$$\frac{i_{D2}}{i_{D1}} = e^{DV/nV_T} = e^{0.01/n(0.025)}$$

$$= \begin{cases} 1.492 & \sim n=1 \\ 1.221 & \sim n=2 \end{cases}$$

$$\% \text{ CHANGE} = \frac{i_{D2} - i_{D1}}{i_{D1}} \times 100$$

$$= \begin{cases} (1.492 - 1) \times 100 = \underline{\underline{+49.2\%}} & n=1 \\ (1.221 - 1) \times 100 = \underline{\underline{22.1\%}} & n=2 \end{cases}$$

FOR A -10mV CHANGE

$$\frac{i_{D2}}{i_{D1}} = 10^{-0.01/n(0.025)} = \begin{cases} 0.670 & n=1 \\ 0.819 & n=2 \end{cases}$$

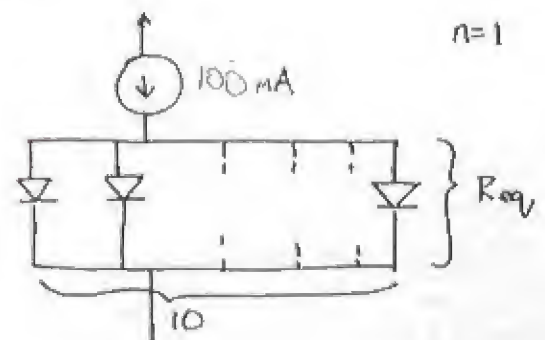
$$\% \text{ CHANGE} = \begin{cases} (0.670 - 1) \times 100 = \underline{\underline{-33\%}} & n=1 \\ (0.819 - 1) \times 100 = \underline{\underline{-18\%}} & n=2 \end{cases}$$

For a current change limited to $\pm 10\%$

$$\frac{i_{D2}}{i_{D1}} = e^{DV/n \times 0.015} = 0.9 \text{ to } 1.1$$

$$DV = \begin{cases} -2.634 \text{ mV to } 2.383 \text{ mV} & n=1 \\ -5.268 \text{ mV to } 4.766 \text{ mV} & n=2 \end{cases}$$

3.53



Each diode has the current

$$i_D = \frac{0.1}{10} = 0.01 \text{ A}$$

Each diode has a small-signal resistance

$$r_d = \frac{nV_T}{I_D} = \frac{0.025}{0.01} = \underline{\underline{2.5 \Omega}}$$

$$R_{eq} = r_d/10 = \underline{\underline{0.25 \Omega}}$$

For one diode conducting 0.1 A

$$r_d = nV_T/0.1 = \frac{0.025}{0.1} = \underline{\underline{0.25 \Omega}}$$

This is the same as R_{eq} . We can think of the parallel connection as equivalent to a single diode having 10 times the junction area of each diode. This large diode

is fed with $10\times$ the current (or $0.1A$) and this exhibits the same small-signal resistance as 10 parallel smaller diodes.

Now consider the series resistance of 0.2Ω to connect a diode. For the parallel combination above:

$$R_{eq} = \frac{1}{10} (0.2 + 2.5) = 0.27\Omega$$

To have an equivalent resistance, the single diode conducting all of the $0.1A$ would need a series resistance $10\times$ as small or 0.02Ω . Specifically:

$$r_{out} = r_s + r_d = 0.27$$

$$= r_s + \frac{nV_T}{I_D} = 0.27$$

$$= r_s + 0.25 = 0.27$$

$$r_s = 0.27 - 0.25 = \underline{\underline{0.02\Omega}}$$



$$r_d = \frac{nV_T}{I}$$

$$n=2$$

Now:

$$V_o = V_s \frac{r_d}{r_d + R_s}$$

$$= V_s \frac{\frac{nV_T}{I}}{\frac{nV_T}{I} + R_s} = V_s \frac{nV_T}{nV_T + IR_s}$$

Q.E.D.

$$V_o = 10mV \frac{0.05}{0.05 + 10^3 I}$$

$$= \begin{cases} 0.476mV & \sim I = 1mA \\ 3.333mV & \sim I = 0.1mA \\ 9.804mV & \sim I = 1\mu A \end{cases}$$

$$\text{For } V_o = \frac{1}{2} V_s = V_s \times \frac{0.05}{0.05 + 10^3 I}$$

$$I = \underline{\underline{50\mu A}}$$

3.55

$R_s = 10k\Omega$, $n=1$, a $1mA$ diode

$$V_o/V_i = \frac{0.025}{0.025 + R_s I}$$

$$= \frac{0.025}{0.025 + 10^4 I} \quad (1)$$

For the current change limited to $\pm 10\%$ of I & using the exponential model we get

$$\frac{i_{02}}{i_{01}} = e^{\Delta V/nV_T} = 0.9 \text{ to } 1.1$$

CONT.

3.54



SMALL
SIGNAL
EQUIVALENT
CIRCUIT

To find the small-signal response, V_o , open the dc current source I , and short the capacitors C_1 and C_2 . Also replace the diode with its small signal resistance:

$$\Delta V = \underline{-2.63 \text{ mV to } 2.38 \text{ mV}}$$

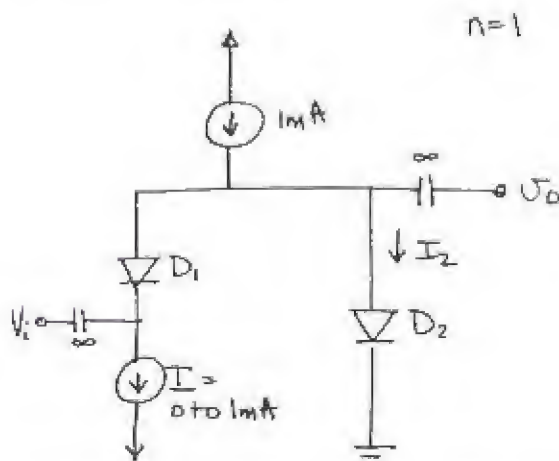
This is the amount the output will vary for a 10% change in diode current. Divide this by the specific gains given in the problem to find the limit on the input signal.

$$\Delta V_s = \frac{\Delta V_o}{V_o/V_I}$$

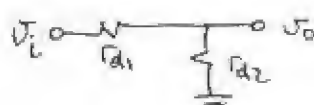
$$= \frac{-2.63 \text{ mV}}{\Delta V_o/V_I} \text{ to } \frac{2.38 \text{ mV}}{V_o/V_I} \text{ (2)}$$

V_o/V_I	$I_{\text{use}} \text{ (mA)} \text{ (1)}$	$V_s \text{ (using (2)) (mV)}$
0.5	0.0025	5.26 to 4.76
0.1	0.0225	26.3 to 23.8
0.01	0.25	263 to 238
0.001	2.5	2630 to 2380

3.56



small signal model when D_1 & D_2 are conducting



(a) $I = 0 \mu\text{A}$

D_1 - cutoff $\Rightarrow \frac{V_o}{V_I} = 0 \text{ V/V}$
 $I_2 = 1 \text{ mA}$

(b) $I = 1 \mu\text{A}$ $I_2 = 999 \mu\text{A}$

$$r_{d1} = \frac{nV_T}{I} \quad r_{d2} = \frac{0.025}{999 \times 10^{-6}}$$

$$= \frac{0.025}{I} \quad = 25.025 \Omega$$

$$= 25 \Omega$$

$$\frac{V_o}{V_I} = \frac{r_{d2}}{r_{d1} + r_{d2}} = \underline{0.001 \frac{\text{V}}{\text{V}}}$$

(c) $I = 10 \mu\text{A}$ $I_2 = 990 \mu\text{A}$

$$r_{d1} = \frac{0.025}{10 \times 10^{-6}} \quad r_{d2} = \frac{0.025}{990 \times 10^{-6}}$$

$$= 2.5 \text{ k}\Omega \quad = 25.25 \Omega$$

$$\frac{V_o}{V_I} = \underline{0.01 \text{ V/V}}$$

(d) $I = 100 \mu\text{A}$

$I_2 = 900 \mu\text{A}$

$$r_{d1} = \frac{0.025}{100 \times 10^{-6}} \quad r_{d2} = \frac{0.025}{900 \times 10^{-6}}$$

$$= 250 \Omega \quad = 27.78 \Omega$$

$$\frac{V_o}{V_I} = \underline{0.1 \text{ V/V}}$$

(e) $I = 500 \mu\text{A}$

$I_2 = 500 \mu\text{A}$

$$r_{d1} = r_{d2} = \frac{0.025}{500 \times 10^{-6}} = 50 \Omega$$

$$\frac{V_o}{V_I} = \underline{\frac{1}{2} \text{ V/V}}$$

(f) $I = 600 \mu\text{A}$

$I_2 = 400 \mu\text{A}$

$$r_{d1} = \frac{0.025}{600 \times 10^{-6}} \quad r_{d2} = \frac{0.025}{400 \times 10^{-6}}$$

$$= 41.67 \Omega \quad = 62.5 \Omega$$

IF THE BIAS CURRENT IN EACH
DIODE IS $\geq 10 \mu A$, THE DIODE RESISTANCE
MUST BE $\leq 2.5 k\Omega$. TO LIMIT THE
CURRENT SIGNAL TO A MAXIMUM OF 10%
BIAS, THE CURRENT SIGNAL MUST BE
 $1 \mu A$. THUS, THE SIGNAL VOLTAGE ACROSS
A "STARVED" DIODE WILL BE
10 mV WHICH IS APPROXIMATELY THE
VOLTAGE TO WHICH THE INPUT SIGNAL
VOLTAGE SHOULD BE LIMITED.

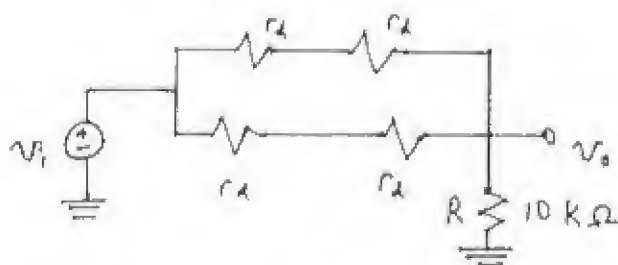
3.57

$$(a) \frac{v_o}{v_i} = \frac{R}{R + (2r_d // 2r_d)}$$

$$= \frac{R}{R + r_d}$$

$$\text{WHERE } r_d = \frac{V_T}{I/2} = \frac{2V_T}{I}$$

$$= \frac{0.05 \text{ V}}{I}$$



$I \text{ (mA)}$	$v_o/v_i \text{ (V/V)}$
0	0
10^{-3}	0.167
0.01	0.667
0.1	0.952
1.0	0.995
10	0.9995

(b) IF THE SIGNAL CURRENT IS TO BE LIMITED TO $\pm 10I$, THE CHANGE IN DIODE VOLTAGE Δv_D CAN BE FOUND FROM

$$\frac{i_D}{I} = e^{\Delta v_D / nV_T} = 0.9 \text{ TO } 1.1$$

THUS, FOR $n=1$

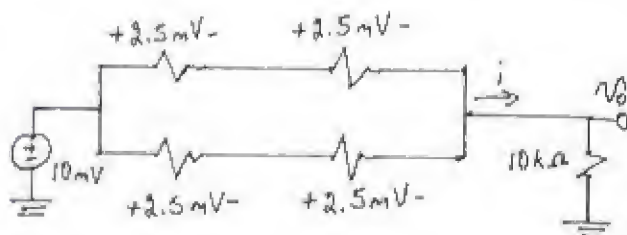
$$\Delta v_D = -2.63 \text{ mV TO } +2.38 \text{ mV}$$

OR APPROXIMATELY $\pm 2.5 \text{ mV}$

CONT.

3.57 CONT.

(b CONT.) FOR THE DIODE CURRENT TO REMAIN WITHIN $\pm 10\%$ OF THEIR dc BIAS CURRENTS, THE SIGNAL VOLTAGE ACROSS EACH DIODE MUST BE LIMITED TO 2.5 mV . NOW, IF $v_{i\text{PEAK}} = 10 \text{ mV}$ WE CAN OBTAIN THE FOLLOWING SITUATION



WE SEE THAT $v_o = 5 \text{ mV}$ AND

$$i = \frac{5 \text{ mV}}{10 \text{ k}\Omega} = 0.5 \mu\text{A}$$

THUS, EACH DIODE IS CARRYING A CURRENT SIGNAL OF 0.25 mA . FOR THIS TO BE AT MOST 10% OF THE dc CURRENT, THE dc CURRENT IN EACH DIODE MUST BE AT LEAST $2.5 \mu\text{A}$. IT FOLLOWS THAT THE MINIMUM VALUE OF I MUST BE $5 \mu\text{A}$.

(c) FOR $I = 1 \text{ mA}$, $I_D = 0.5 \text{ mA}$, AND FOR MAXIMUM SIGNAL OF 10% , $I_D = 0.05 \text{ mA}$. THUS $i_D = 2i_d = 0.1 \text{ mA}$ AND THE CORRESPONDING MAXIMUM v_o IS $0.1 \text{ mA} \times 10 \text{ k}\Omega = 1 \text{ V}$.

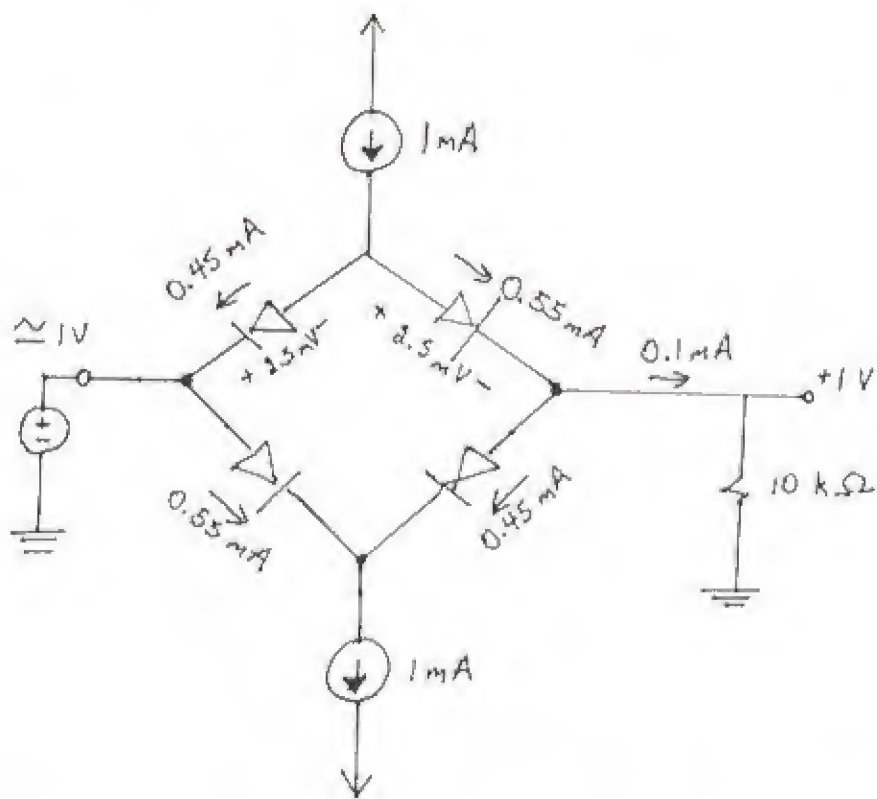
THE CORRESPONDING PEAK INPUT CAN BE FOUND BY DIVIDING v_o BY THE TRANSMISSION FACTOR OF 0.995 , THUS

$$v_{i\text{MAX}} = \frac{1 \text{ V}}{0.995} = \underline{\underline{1.005 \text{ V}}}$$

SEE FIGURE.

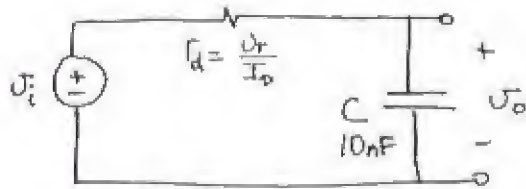
EACH DIODE HAS $r_d = 50 \Omega$

3.57 CONT.



3.58

Opening the current source we get the following small-signal circuit:
($n=1$)



$$\frac{V_o}{V_i} = \frac{Y_{sc}}{Y_{sc} + r_d} = \frac{1}{1 + sCr_d}$$

$$\text{Phase Shift} = -\tan^{-1}\left(\frac{\omega Cr_d}{1}\right)$$

$$= -\tan^{-1}\left(2\pi \cdot 10^5 \times 10 \times 10^{-9} \times 0.025/I\right)$$

For a phase shift of -45° we have

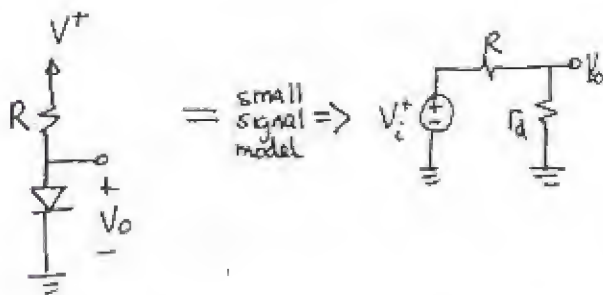
$$2\pi \cdot 10^5 \times 10(10^{-9}) \times \frac{0.025}{I} = 1$$

$$I = \underline{157 \mu A}$$

Range of phase shift for $I = 15.7 \mu A$ to $1570 \mu A$ is :

$$\underline{-84.3^\circ \text{ to } -5.71^\circ}$$

3.59



CONT.

$$\begin{aligned}
 (a) \quad \frac{\Delta V_o}{\Delta V^+} &= \frac{r_d}{r_d + R} = \frac{nV_T/I}{nV_T/I + R} \\
 &= \frac{nV_T}{nV_T + IR} \quad \text{where at No load} \\
 &\quad I = \frac{V^+ - 0.7}{R} \\
 &= \frac{nV_T}{nV_T + V^+ - 0.7} \quad \text{Q.E.D.}
 \end{aligned}$$

(b) For m diodes in series use

$$I = \frac{V^+ - m \times 0.7}{R}$$

Thus:

$$\begin{aligned}
 \frac{\Delta V_o}{\Delta V^+} &= \frac{m r_d}{m r_d + R} = \frac{m(nV_T)}{m(nV_T) + IR} \\
 &= \frac{m(nV_T)}{m(nV_T) + V^+ - 0.7m}
 \end{aligned}$$

(c) Line Regulation for $V^+ = 10V$, $n=2$

$$i) \quad m=1 \quad \frac{\Delta V_o}{\Delta V^+} = \underline{\underline{5.35 \text{ mV/V}}}$$

$$ii) \quad m=3 \quad \frac{\Delta V_o}{\Delta V^+} = \underline{\underline{18.63 \text{ mV/V}}}$$

$$\Delta V_o = -I_L (R \parallel r_d)$$

$$\frac{\Delta V_o}{I_L} = \underline{\underline{-(R \parallel r_d)}} \quad \text{Q.E.D.}$$

(b) Given at DC $I_D = \frac{V^+ - 0.7}{R}$

$$\text{Also } r_d = \frac{nV_T}{I_D}$$

We have:

$$\frac{\Delta V_o}{I_L} = - \frac{1}{\frac{1}{R} + \frac{1}{r_d}}$$

$$= - \frac{1}{\frac{I_D}{V^+ - 0.7} + \frac{I_D}{nV_T}}$$

$$= - \frac{nV_T}{I_D} \frac{1}{1 + \frac{nV_T}{V^+ - 0.7}}$$

$$= - \frac{nV_T}{I_D} \frac{V^+ - 0.7}{V^+ - 0.7 + nV_T} \quad \text{Q.E.D.}$$

$$\text{for } \frac{\Delta V_o}{I_L} \leq 5 \frac{\text{mV}}{\text{mA}}$$

$$\frac{-2 \times 0.025}{I_D} \times \frac{10 - 0.7}{10 - 0.7 + 2 \times 0.05} \leq \frac{5 \times 10^{-3}}{10^{-3}}$$

$$I_D \gg 9.947 \text{ mA} \Rightarrow I_D = \underline{\underline{10 \text{ mA}}}$$

$$R = \frac{V^+ - 0.7}{I_D} = \frac{10 - 0.7}{10} = \underline{\underline{930 \Omega}}$$

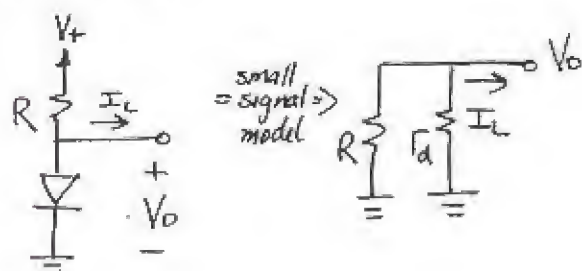
Thus the diode should be a 10mA diode.

(c) For m diodes

$$I_D = \frac{V^+ - 0.7m}{R} \quad \& \quad r_d = \frac{m(nV_T)}{I_D}$$

CONST.

3.60



$$\frac{\Delta V_o}{I_L} = \frac{-1}{\frac{1}{R} + \frac{1}{g_d}}$$

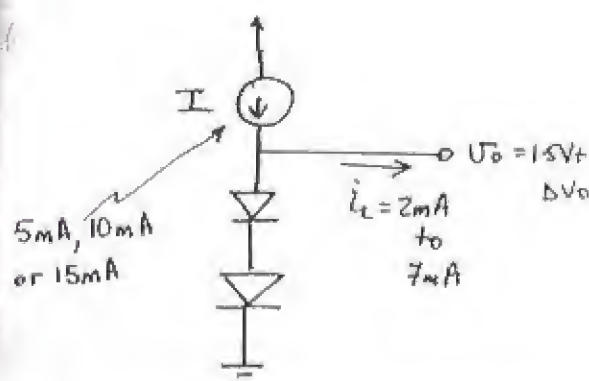
$$= \frac{-1}{\frac{I_D}{V^+ - 0.7m} + \frac{I_D}{mnV_T}}$$

$$= -\frac{mnV_T}{I_D} \frac{1}{\frac{mnV_T}{V^+ - 0.7m} + 1}$$

$$= \frac{-mnV_T}{I_D} \frac{V^+ - 0.7m}{V^+ - 0.7m + mnV_T}$$

3.61

3.62



For a load current of 2 to 7 mA, I must be greater than 7 mA. Thus the 5 mA source would not do.

We are left to choose between the 10 and 15 mA sources. The 15 mA source provides lower load regulation because the diodes will have more current flowing through them at all times. This is shown below:

Load Regulation if $I = 10 \text{ mA}$

$$\text{use } \frac{I_{D2}}{I_{D1}} = e^{\frac{\Delta V / 2 \times nVT}{1}} \quad \text{2 diodes}$$

$$\text{so } e^{\frac{\Delta V / 0.05 \times 2}{1}} = 3/10 \text{ to } 8/10$$

$$\Delta V_O = -120 \text{ mV to } -22.3 \text{ mV}$$

∴ The peak to peak ripple is $-120 - (-22.3) \approx -100 \text{ mV}$

$$\text{Load Regulation} = \frac{\Delta V_O}{I_L} = \frac{-100}{5}$$

$$= -20 \frac{\text{mV}}{\text{mA}}$$

Load Regulation for $I = 15 \text{ mA}$.

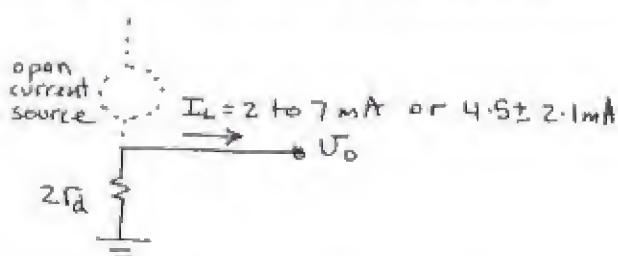
Here the current through the diodes change from 8 to 13 mA corresponding to

$$\Delta V_O = 0.1 \ln(8/13) = -49 \text{ mV}$$

$$\text{Load Regulation} = \frac{-49}{5} \approx -10 \frac{\text{mV}}{\text{mA}}$$

The obvious disadvantage of using the 15 mA supply is the requirement of higher current and higher power dissipation.

Alternate solution of Line Regulation using the small signal model



$$\text{Load Regulation} = \frac{\Delta V_O}{I_L} = -2r_d = -\frac{2nVT}{I_D}$$

Where the bias current $I_D = 10 - 4.5$ for the 10 mA source.

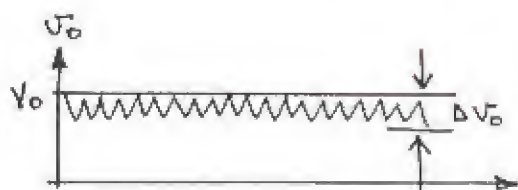
$$\Rightarrow \frac{\Delta V_O}{I_L} = \frac{-2 \times 2 \times 0.025}{10 - 4.5} = -18.2 \frac{\text{mV}}{\text{mA}}$$

For 15 mA source $I_D = 15 - 4.5$

$$\frac{\Delta V_O}{\Delta I_L} = \frac{-0.1}{15 - 4.5} = -9.5 \frac{\text{mV}}{\text{mA}}$$

CONT.

Sketch of output:-



3.63

3.64

$$\begin{aligned} (a) \quad V_z &= V_{z0} + r_z I_{zT} \\ 10 &= 9.6 + r_z \times 50 \times 10^{-3} \\ r_z &= \underline{8 \Omega} \end{aligned}$$

Power rating:

$$\begin{aligned} V_z &= V_{z0} + r_z \times 2I_{zT} \\ &= 9.6 + 8 \times 100 \times 10^{-3} \\ &= 10.4 \text{ V} \end{aligned}$$

$$P = 10.4 \times 100 \times 10^{-3} = \underline{1.04 \text{ W}}$$

$$\begin{aligned} (b) \quad V_z &= V_{z0} + r_z I_{zT} \\ 9.1 &= V_{z0} + 30 \times 10 \times 10^{-3} \\ V_{z0} &= \underline{8.8 \text{ V}} \end{aligned}$$

$$\begin{aligned} V_z &= 8.8 + 30 \times 20 \times 10^{-3} = 9.4 \text{ V} \\ P &= 9.4 \times 20 \times 10^{-3} = \underline{188 \text{ mW}} \end{aligned}$$

$$\begin{aligned} (c) \quad 6.8 &= 6.6 + 2 \times I_{zT} \\ I_{zT} &= \underline{100 \text{ mA}} \end{aligned}$$

$$\begin{aligned} V_z &= 6.6 + 2 \times 200 \times 10^{-3} = 7 \text{ V} \\ P &= 7 \times 200 \times 10^{-3} = \underline{1.4 \text{ W}} \end{aligned}$$

$$\begin{aligned} (d) \quad 18 &= 17.2 + r_z \times 5 \times 10^{-3} \\ r_z &= \underline{160 \Omega} \end{aligned}$$

$$\begin{aligned} V_z &= 17.2 + 160 \times 10 \times 10^{-3} = 18.8 \text{ V} \\ P &= 18.8 \times 10 \times 10^{-3} = \underline{188 \text{ mW}} \end{aligned}$$

$$\begin{aligned} (e) \quad 7.5 &= V_{z0} + 1.5 \times 200 \times 10^{-3} \\ V_{z0} &= \underline{7.2 \text{ V}} \end{aligned}$$

$$\begin{aligned} V_z &= 7.2 + 1.5 \times 400 \times 10^{-3} = 7.8 \text{ V} \\ P &= 7.8 \times 400 \times 10^{-3} = \underline{3.12 \text{ W}} \end{aligned}$$

3.65

(a) Three 6.8 V zeners provide $3 \times 6.8 = 20.4 \text{ V}$ with $3 \times 10 = 30 \Omega$ resistance. Neglecting R , we have

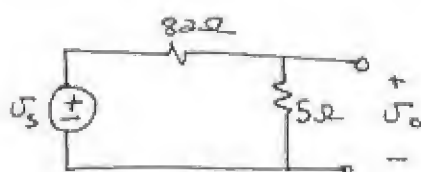
$$\text{Load Regulation} = \underline{-30 \text{ mV/mA}}$$

(b) For 5.1 V zeners we use 4 diodes to provide 20.4 V with $4 \times 30 = 120 \Omega$ resistance.

$$\text{Load regulation} = \underline{-120 \text{ mV/mA}}$$

3.66

Small signal model for line regulation:



$$\frac{\Delta V_o}{\Delta V_s} = \frac{5}{5 + 82}$$

$$\Delta V_o = \frac{5}{87} \times \Delta V_s$$

$$= \frac{5}{87} \times 1.3$$

$$= \underline{74.7 \text{ mV}}$$

3.67

$$V_Z = V_{Z0} + r_Z I_{ZT}$$

$$9.1 = V_{Z0} + 5 \times 28 \times 10^{-3}$$

$$V_{Z0} = 8.96V$$

$$V_Z = V_{Z0} + 5I_Z = 8.96 + 5I_Z$$

$$\text{For } I_Z = 10mA \quad V_Z = \underline{\underline{9.01V}}$$

$$\text{For } I_Z = 100mA \quad V_Z = \underline{\underline{9.46V}}$$

3.68

$$r_z = 30 \Omega$$

$$I_{ZK} = 0.5 \text{ mA}$$

$$V_Z = 7.5 \text{ V}$$

$$I_Z = 12 \text{ mA}$$

$$7.5 = V_{Z0} + 12 \times 30 \times 10^{-3}$$

$$\Rightarrow V_{Z0} = 7.14 \text{ V}$$

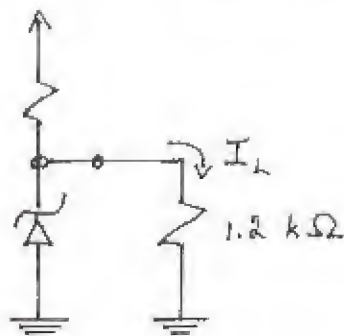
$$I_Z = \frac{7.5}{1.2} = 6.25 \text{ mA}$$

SELECT $I = 10 \text{ mA}$

SO THAT $I_Z = 3.7 \text{ mA}$

WHICH IS $> I_{ZK}$

$$R = \frac{10 - 7.5}{10} = \underline{\underline{250 \Omega}}$$



For $\Delta V^+ = \pm 1 \text{ V}$

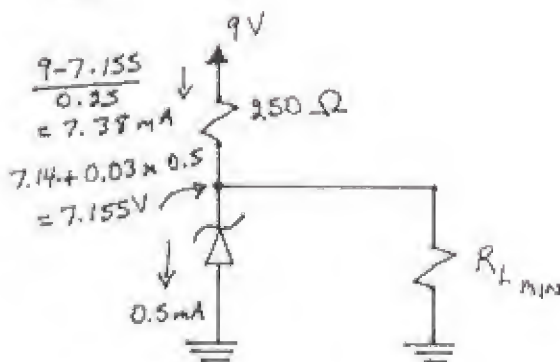
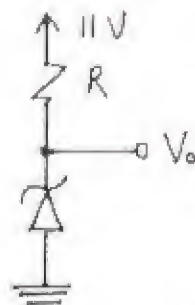
$$\Delta V_o = \pm 1 \times \frac{1.2 // 0.03}{0.250 + (1.2 // 0.03)}$$

$$= \pm 0.1 \text{ V}$$

THUS $V_o = +7.4 \text{ V TO } +7.6 \text{ V}$
WITH $V^+ = 11 \text{ V}$ AND $I_L = 0$

$$V_o = V_{Z0} + \frac{11 - V_o}{0.25} \times 0.03$$

$$\Rightarrow V_o = \underline{\underline{7.55 \text{ V}}}$$



$$R_{L \min} = \frac{7.155}{7.38 - 0.5}$$

$$= \underline{\underline{1.04 \text{ k}\Omega}}$$

$$\therefore R = \frac{9 - 0.68}{20} = \underline{\underline{110 \Omega}}$$

$$\begin{aligned} \text{Line Regulation} &= \frac{\Delta V_o}{\Delta V_s} = \frac{r_z}{r_z + R} \\ &= \frac{5}{5 + 110} \\ &= \underline{\underline{43.5 \frac{mV}{V}}} \end{aligned}$$

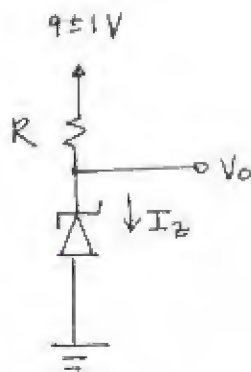
SECOND DESIGN ~ limited current from 9V supply

$$I_z = 0.25 \text{ mA}$$

$$\begin{aligned} V_z &= V_{zk} \approx V_{zo} - \text{calculate } V_{zo} \text{ from} \\ V_z &= V_{zo} + r_z I_{zT} \\ 6.8 &= V_{zo} + 5 \times 0.02 \\ V_{zo} &= 6.7 \text{ V} \end{aligned}$$

$$\therefore R = \frac{9 - 6.7}{0.25} = \underline{\underline{9.2 \text{ k}\Omega}}$$

3.69



Given Parameters

$$V_z = 6.8 \text{ V}, r_z = 5 \Omega, I_z = 20 \text{ mA}$$

By knee

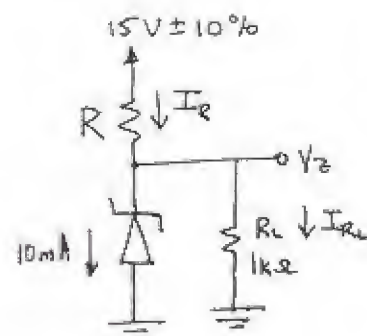
$$I_{zk} = 0.25 \text{ mA}, r_z = 750 \Omega$$

FIRST DESIGN - 9V supply can easily supply current

Let $I_z = 20 \text{ mA}$ ~ well above knee

$$\begin{aligned} \text{Line Regulation} &= \frac{\Delta V_o}{\Delta V_s} = \frac{750}{750 + 9200} \\ &= \underline{\underline{75.4 \frac{mV}{V}}} \end{aligned}$$

3.70



$$\begin{aligned} V_z &= V_{zo} + r_z I_z \\ 9.1 &= V_{zo} + 30(0.009) \\ V_{zo} &= \underline{\underline{8.83 \text{ V}}} \end{aligned}$$

CONT.

$$V_z = 8.83 + 30(0.01) = 9.13 \text{ V}$$

$$I_{R_L} = 9.13 / 1 \text{ k}\Omega = 9.13 \text{ mA}$$

$$I_x = 10 + 9.13 = \underline{19.13 \text{ mA}}$$

$$\therefore R = \frac{15 - 9.13}{19.13} = 306.8 \Omega$$

$$\approx \underline{300 \Omega}$$

$$V_z = 8.83 + 30 \left(\frac{15 - V_z}{300} - \frac{V_z}{1000} \right)$$

$$= 10.33 - V_z/10 - 3/100 V_z$$

$$V_z = 9.14 \text{ V}$$

$$V_z = 8.83 + 30 \left(\frac{15 \pm 0.15 - V_z}{300} - \frac{V_z}{1000} \right)$$

$$= \frac{1}{1.13} [8.83 + 15 \pm 0.15] = 9.14 \pm 0.13 \text{ V}$$

$\pm 0.13 \text{ V}$ variation in output voltage
Halving the load current $\approx R_L$ doubling

$$V_z = 8.83 + 30 \left(\frac{15 - V_z}{300} - \frac{V_z}{2000} \right)$$

$$= \frac{10.33}{1.115} = 9.26 \text{ V}$$

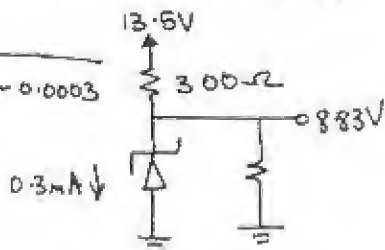
$\therefore 9.26 - 9.14 = 0.12 \text{ V}$ increase in output voltage.

At the edge of the breakdown region

$$V_z \approx V_{z0} = 8.83 \text{ V} \quad I_{zK} = 0.3 \text{ mA}$$

$$R_L = \frac{8.83}{\frac{13.5 - 8.83}{300} - 0.0003}$$

$$= \underline{578 \Omega}$$



Lowest output voltage = 8.83 V

$$\text{Line Regulation} = \frac{r_z}{R + r_z} = \frac{30}{300 + 30}$$

$$= 90 \frac{\text{mV}}{\text{V}}$$

$$\text{Load Regulation} = -(r_z \parallel R) = -29.1 \frac{\text{mV}}{\text{mA}}$$

3.71

$$(a) V_{zT} = V_{z0} + r_z I_{zT}$$

$$10 = V_{z0} + 7(0.025)$$

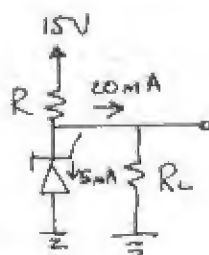
$$\Rightarrow V_{z0} = \underline{9.825 \text{ V}}$$

(b) The minimum Zener current of 5mA occurs when $I_L = 20 \text{ mA}$ and V_s is at its minimum of $20(1 - 0.25) = 15 \text{ V}$. See the circuit below:

$$R \leq \frac{15 - (V_{z0} + r_z I_L)}{20 + 5}$$

$$\leq \frac{15 - (9.825 + 7(0.005))}{25}$$

$$\leq 205.6 \Omega$$



\therefore Use $R = \underline{205 \Omega}$

$$(c) \text{Line Regulation} = \frac{r_z}{205 + 7} = 33 \frac{\text{mV}}{\text{V}}$$

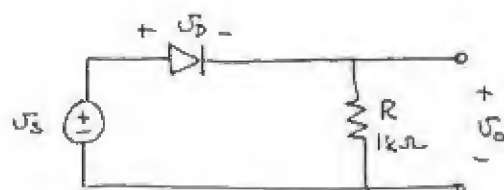
$\pm 25\%$ change in $V_s \approx \pm 5 \text{ V}$

$$V_o \text{ changes by } \pm 5 \times 33 = \underline{\pm 165 \text{ mV}}$$

$$\text{corresponding to } \frac{\pm 165}{10} \times 100 = \underline{\pm 1.65\%}$$

CONT.

3.75



$$i_D = I_S e^{V_D / nV_T}$$

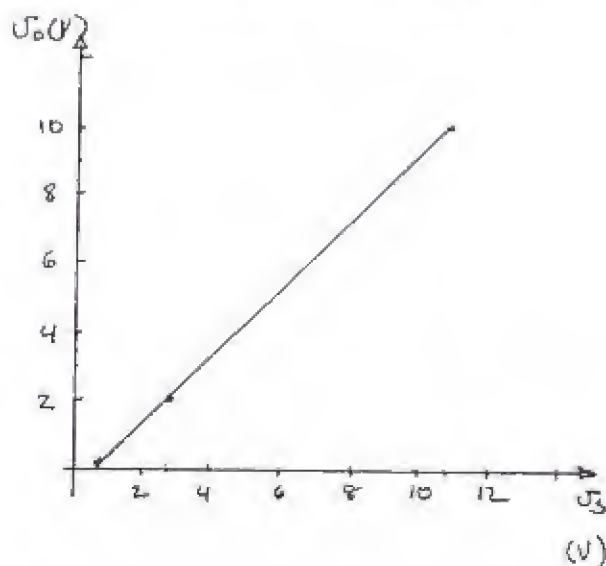
$$\frac{i_D}{1\text{mA}} = e^{\frac{V_D - 0.7}{nV_T}}$$

$$V_D - 0.7 = nV_T \ln(i_D / 10^{-3}) = 0.1 \log\left(\frac{i_D}{10^{-3}}\right)$$

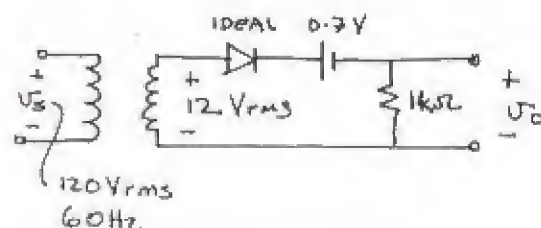
$$V_D = 0.7 + 0.1 \log\left(\frac{V_o}{R}\right) \quad R = 1k\Omega$$

$$= 0.7 + 0.1 \log\left(\frac{V_o}{1}\right)$$

V_o (V)	V_D (V)	$V_s = V_D + V_o$ (V)
0.10	0.6	0.7
0.5	0.67	1.17
1	0.7	1.7
2	0.73	2.73
5	0.77	5.77
10	0.8	10.8



3.76



$$V_o = 12\sqrt{2} - 0.7 = \underline{16.27\text{V}}$$

Conduction begins at

$$V_s = 12\sqrt{2} \sin \theta = 0.7$$

$$\theta = \sin^{-1}\left(\frac{0.7}{12\sqrt{2}}\right)$$

$$= 0.0412 \text{ rad}$$

Conduction ends at $\pi - \theta$

$$\therefore \text{Conduction angle} = \pi - 2\theta = \underline{3.06 \text{ rad}}$$

The diode conducts for

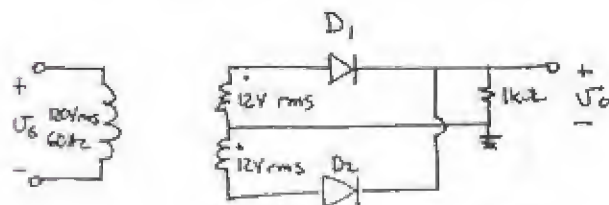
$$\frac{3.06}{2\pi} \times 100 = \underline{48.7\%} \text{ of the cycle}$$

$$V_o, \text{avg} = \frac{1}{2\pi} \int_0^{\pi - 2\theta} 12\sqrt{2} \sin \phi - 0.7 \, d\phi$$

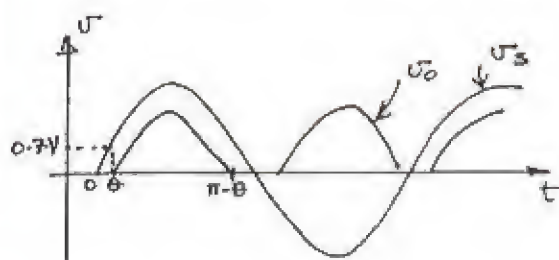
$$= \underline{5.06\text{V}}$$

$$i_{D, \text{avg}} = \frac{V_o, \text{avg}}{R} = \underline{5.06\text{mA}}$$

3.77



CONT.



$$\hat{U}_D = 12\sqrt{2} - V_{D0} = \underline{\underline{16.27V}}$$

Conduction starts at $\theta = \sin^{-1} \frac{0.7}{12\sqrt{2}}$
 $= 0.0412 \text{ rad}$

and ends at $\pi - \theta$. Conduction angle
 $= \pi - 2\theta = 3.06 \text{ rad}$ in each half
 cycle. Thus the fraction of a
 cycle for which one of the two
 diodes conduct $= \frac{2(3.06)}{2\pi} \times 100$
 $= \underline{\underline{97.4\%}}$

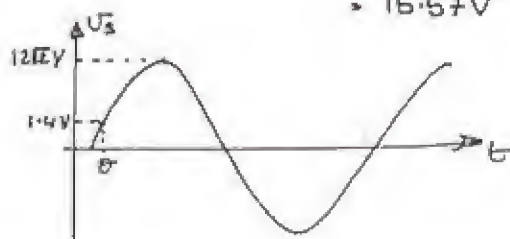
Note that during 97.4% of the cycle
 there will be conduction. However
 each of the two diodes conducts for
 only half the time, i.e. for
 48.7% of the cycle.

$$U_{D, \text{avg}} = \frac{1}{\pi} \int_{\theta}^{\pi-\theta} 12\sqrt{2} \sin \phi - 0.7 \, d\phi$$

$$= \underline{\underline{10.12V}}$$

$$i_{D, \text{avg}} = \frac{10.12}{1k\Omega} = \underline{\underline{10.12 \text{ mA}}}$$

Peak voltage across $R = 12\sqrt{2} - 2V_D$
 $= 12\sqrt{2} - 1.4$
 $= \underline{\underline{15.57V}}$



$$\theta = \sin^{-1} \frac{1.4}{12\sqrt{2}} = 0.0826 \text{ rad}$$

Fraction of cycle that D_1 & D_2 conduct
 is $\frac{\pi - 2\theta}{2\pi} \times 100 = \underline{\underline{47.4\%}}$

Note D_3 & D_4 conduct in the other
 half cycle so that there is $2(47.4) =$
 94.8% conduction interval.

$$U_{D, \text{avg}} = \frac{1}{2\pi} \int_{\theta}^{\pi-\theta} 12\sqrt{2} \sin \phi - 2V_D \, d\phi$$

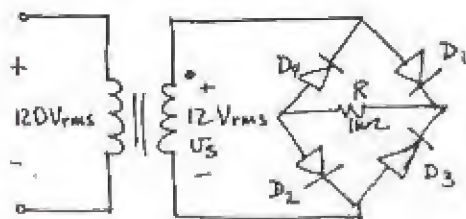
$$= \frac{1}{\pi} \left[-12\sqrt{2} \cos \phi - 1.4 \phi \right]_{\theta}^{\pi-\theta}$$

$$= \frac{2(12\sqrt{2} \cos \theta)}{\pi} - \frac{1.4(\pi - 2\theta)}{\pi}$$

$$= \underline{\underline{9.44V}}$$

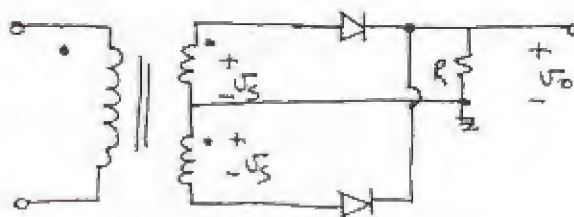
$$i_{R, \text{avg}} = \frac{U_{D, \text{avg}}}{R} = \frac{9.44}{1} = 9.44 \text{ mA}$$

3.78



$$V_D = 0.7V$$

3.79



CONT.

For $V_{D0} \ll V_s$,

$$V_{0, \text{avg}} \approx \frac{2}{\pi} V_s - V_{D0}$$

(a) For $V_{0, \text{avg}} = 10V$

$$10 = \frac{2}{\pi} V_s - 0.7$$

$$\Rightarrow V_s = 16.81V$$

$$\text{Line peak} = 120\sqrt{2}$$

Thus,

$$\text{turns ratio} = \frac{120\sqrt{2}}{16.81} = 10.1:1$$

to each half
of the secondary

OR 5.05:1 centre tapped

(b) For $V_{0, \text{avg}} = 100V$

$$V_s = \frac{\pi}{2} (100.7) = 158.2V$$

$$\text{Turns Ratio} = \frac{120\sqrt{2}}{158.2} = 1.07:1 \text{ to each half}$$

OR 0.535:1 centre tapped

3.80

Refer to Fig 3.27.

For $2V_{D0} \ll V_s$,

$$V_{0, \text{avg}} = \frac{2}{\pi} V_s - 2V_{D0} = \frac{2}{\pi} V_s - 1.4$$

(a) For $V_{0, \text{avg}} = 10V$

$$V_s = \frac{\pi}{2} \times 11.4 = 17.91V$$

$$\text{Turns Ratio} = \frac{120\sqrt{2}}{17.91} = 9.477 \text{ to } 1$$

(b) For $V_{0, \text{avg}} = 100V$

$$V_s = \frac{\pi}{2} \times 101.4 = 159.3V$$

$$\text{Turns Ratio} = \frac{120\sqrt{2}}{159.3} = 1.065 \text{ to } 1$$

3.81

$$120\sqrt{2} \pm 10\% : 24\sqrt{2} \pm 10\%$$

$$\Rightarrow \text{turns Ratio} = 5:1$$

$$V_s = \frac{24\sqrt{2}}{2} \pm 10\%$$

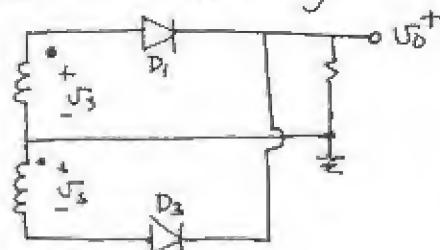
$$\begin{aligned} PIV &= 2V_s|_{\text{max}} - V_{D0} \\ &= 2 \times \frac{24\sqrt{2}}{2} \times 1.1 - 0.7 \end{aligned}$$

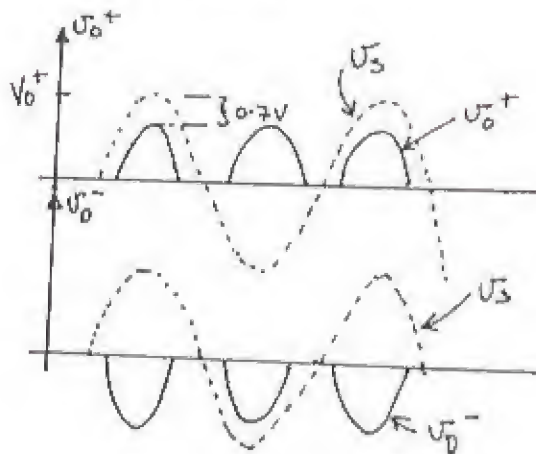
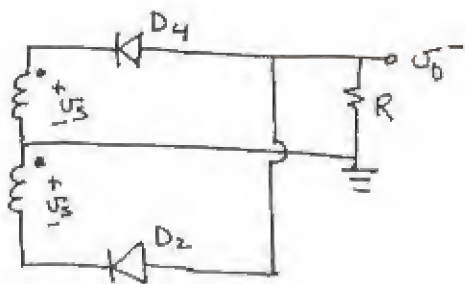
$$= 36.6V$$

Using a factor of 1.5 for safety we select a diode having a PIV rating of 55V

3.82

The circuit is a full wave rectifier with centre tapped secondary winding. The circuit can be analyzed by looking at V_{0+} and V_{0-} separately.





$$U_{o,avg} = \frac{1}{2\pi} \int_0^{2\pi} V_s \sin \phi - 0.7 d\phi = 15$$

$$= \frac{2V_s}{\pi} - 0.7 = 15 \quad \text{assumed } V_s \gg 0.7V$$

$$V_s = \frac{15 + 0.7}{2} \pi = 24.66V$$

Thus voltage across secondary winding
 $= 2V_s = \underline{49.32V}$

Looking at D_4

$$PIV = V_s - V_o^-$$

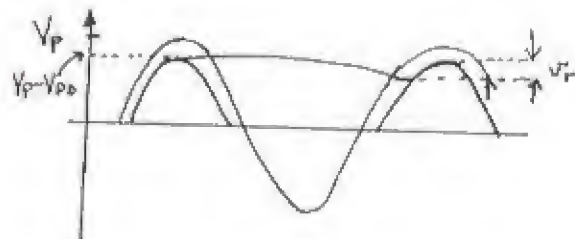
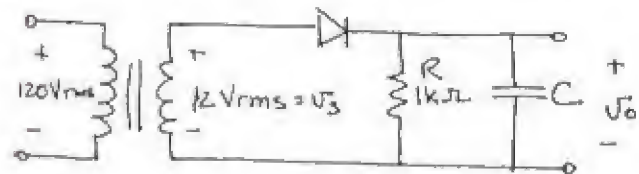
$$= V_s + (V_s - 0.7)$$

$$= 2V_s - 0.7$$

$$= \underline{48.6V}$$

If choosing a diode, allow a safety margin of $1.5 PIV = \underline{73V}$

3.83



$$(i) V_r = (V_p - V_{do}) \frac{T}{CR} \quad \text{Eq. (3.28)}$$

$$0.1(V_p - V_{do}) = (V_p - V_{do}) \frac{T}{CR}$$

$$C = \frac{1}{0.1 \times 60 \times 10^3} = \underline{166.7 \mu F}$$

$$(ii) \text{ For } V_r = 0.01(V_p - V_{do}) = \frac{(V_p - V_{do}) T}{CR}$$

$$C = \underline{1667 \mu F}$$

(a)

$$(i) U_{o,avg} = V_p - V_{do} - \frac{1}{2} V_r$$

$$= 12\sqrt{2} - 0.7 - \frac{1}{2} (12\sqrt{2} - 0.7) 0.1$$

$$= (12\sqrt{2} - 0.7) \left(1 - \frac{0.1}{2}\right)$$

$$= \underline{15.5V}$$

$$(ii) U_{o,avg} = (12\sqrt{2} - 0.7) \left(1 - \frac{0.01}{2}\right)$$

$$= \underline{16.19V}$$

CONT.

(b)

i) Using eq (3.30) we have the conduction angle =

$$\begin{aligned} \omega \Delta t &\approx \sqrt{\frac{2V_r}{V_p - V_{D0}}} \\ &= \sqrt{\frac{2 \times 0.1 (V_p - 0.7)}{(V_p - 0.7)}} \\ &= \sqrt{0.2} \\ &= 0.447 \text{ rad} \end{aligned}$$

• Fraction of cycle for conduction = $\frac{0.447}{2\pi} \times 100$
 $= 7.1\%$

ii) $\omega \Delta t \approx \sqrt{\frac{2 \times 0.01 (V_p - 0.7)}{V_p - 0.7}} = 0.141 \text{ rad}$

Fraction of cycle = $\frac{0.141}{2\pi} \times 100 = 2.25\%$

(c)(i) Use Eq (3.31)

$$\begin{aligned} i_{D, \text{avg}} &= I_L \left(1 + \pi \sqrt{\frac{2(V_p - V_{D0})}{V_r}} \right) \\ &= \frac{V_{D, \text{avg}}}{R} \left(1 + \pi \sqrt{\frac{2(V_p - V_{D0})}{0.1(V_p - V_{D0})}} \right) \\ &= \frac{15.5}{10^3} \left(1 + \pi \sqrt{\frac{2}{0.1}} \right) \\ &= 233 \text{ mA} \end{aligned}$$

ii) $i_{D, \text{avg}} = \frac{16.19}{10^3} \left(1 + \pi \sqrt{200} \right)$
 $= 735 \text{ mA}$

NB Text uses $I_L \approx V_p/R = \frac{V_p - V_{D0}}{R}$
 but here we used $i_{D, \text{avg}} = \frac{V_p - V_{D0} - \frac{1}{2}V_r}{R}$
 which is more accurate.

(d)i) $i_{D, \text{peak}} = I_L \left(1 + 2\pi \sqrt{\frac{2(V_p - V_{D0})}{V_r}} \right)$
 $= \frac{15.42}{10^3} \left(1 + 2\pi \sqrt{\frac{2}{0.1}} \right)$
 $= 449 \text{ mA}$

ii) $i_{D, \text{peak}} = \frac{16.19}{10^3} \left(1 + 2\pi \sqrt{\frac{2}{0.01}} \right)$
 $= 1455 \text{ mA}$

3.84

i) $V_r = 0.1(V_p - V_{D0}) = \frac{(V_p - V_{D0})}{2fCR}$

the factor of 2 accounts for discharge occurring only half of the period $t/2 = \frac{1}{2f}$

$C = \frac{1}{(2fR)0.1} = \frac{1}{2(60)10^3 \times 0.1} = 833 \mu\text{F}$

ii) $C = \frac{1}{2(60)10^3 \times 0.01} = 833 \mu\text{F}$

(a)i) $V_0 = V_p - V_{D0} - \frac{1}{2}V_r$
 $= (V_p - V_{D0}) \left(1 - \frac{0.1}{2} \right)$
 $= (16.27) \left(1 - \frac{0.1}{2} \right)$
 $= 15.5 \text{ V}$

ii) $V_0 = (16.27) \left(1 - \frac{0.01}{2} \right) = 16.19 \text{ V}$

(b)

(i) Fraction of cycle = $\frac{2\omega \Delta t}{2\pi} \times 100$
 $= \frac{\sqrt{2V_r/(V_p - V_{D0})}}{\pi} \times 100$
 $= \frac{1}{\pi} \sqrt{2(0.1)} \times 100 = 14.2\%$

CONST.

$$\text{ii) Fraction of Cycle} = \frac{2\sqrt{2(0.01)}}{2\pi} \times 100$$

$$= \underline{4.5\%}$$

(c) Use eq (3.34)

$$\text{i) } I_{D, \text{avg}} = I_L \left(1 + \pi \sqrt{\frac{V_p - V_{D0}}{2V_r}} \right)$$

$$= \frac{15.5}{1} \left(1 + \pi \sqrt{\frac{1}{2(0.1)}} \right) = \underline{124.4 \text{ mA}}$$

$$\text{ii) } I_{D, \text{avg}} = \frac{16.19}{1} \left(1 + \pi \sqrt{\frac{1}{2(0.01)}} \right) = \underline{376 \text{ mA}}$$

(d) Use eq (3.35)

$$\text{i) } \hat{I}_D = I_L \left(1 + 2\pi \frac{1}{\sqrt{2(0.1)}} \right) = \underline{233 \text{ mA}}$$

$$\text{ii) } \hat{I}_D = I_L \left(1 + 2\pi \frac{1}{\sqrt{0.02}} \right) = \underline{735 \text{ mA}}$$

3.85

$$\text{i) } V_r = 0.1(V_p - V_{D0} \times 2) = \frac{V_p - 2V_{D0}}{2fCR}$$

discharge occurs only over $\frac{1}{2}T = \frac{1}{2f}$

$$C = \frac{(V_p - 2V_{D0})}{(V_p - 2V_{D0})} \frac{1}{2(0.1) f R} = \underline{83.3 \mu\text{F}}$$

$$\text{ii) } C = \frac{1}{2(0.01) f R} = \underline{833 \mu\text{F}}$$

$$\text{(b) Fraction of cycle} = \frac{2\omega \Delta t}{2\pi} \times 100$$

$$= \frac{\sqrt{2(0.1)}}{\pi} \times 100 = \underline{14.2\%}$$

$$\text{ii) Fraction of cycle} = \frac{\sqrt{2(0.01)}}{\pi} \times 100 = \underline{4.5\%}$$

(c) i)

$$I_{D, \text{avg}} = \frac{14.79}{1} \left(1 + \pi \sqrt{\frac{1}{0.2}} \right) = \underline{119 \text{ mA}}$$

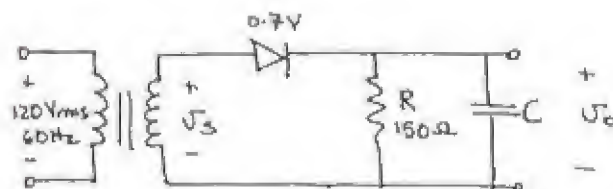
$$\text{ii) } I_{D, \text{avg}} = \frac{15.49}{1} \left(1 + \pi \sqrt{0.02} \right) = \underline{356 \text{ mA}}$$

(d)

$$\text{(i) } \hat{I}_D = \frac{14.79}{1} \left(1 + 2\pi \sqrt{\frac{1}{0.2}} \right) = \underline{223 \text{ mA}}$$

$$\text{(ii) } \hat{I}_D = \frac{15.49}{1} \left(1 + 2\pi \sqrt{\frac{1}{0.02}} \right) = \underline{704 \text{ mA}}$$

3.86



$$V_{o, \text{peak}} = V_p - V_{D0} = 16$$

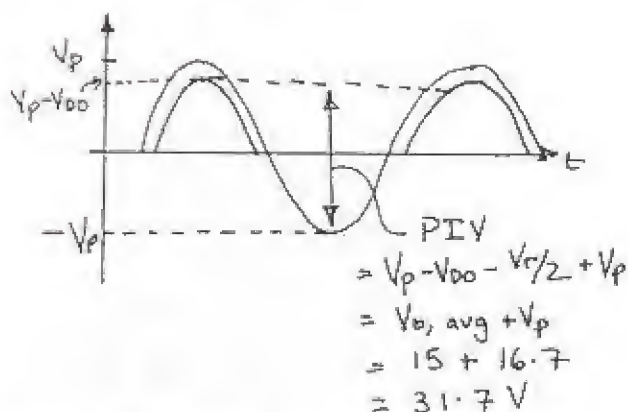
$$V_p = 16.7 \text{ V}$$

$$V_{\text{rms}} = \frac{16.7}{\sqrt{2}} = 11.8$$

$$\text{(b) } V_r = (V_p - V_{D0}) \frac{1}{CR} \quad \text{Eq (3.28)}$$

$$2 = \frac{16}{60 \times C \times 150}$$

$$C = 889 \mu\text{F}$$



$$\text{For a 50\% safety margin } \text{PIV} = 1.5 \times 31.7 = \underline{47.6 \text{ V}}$$

CONT.

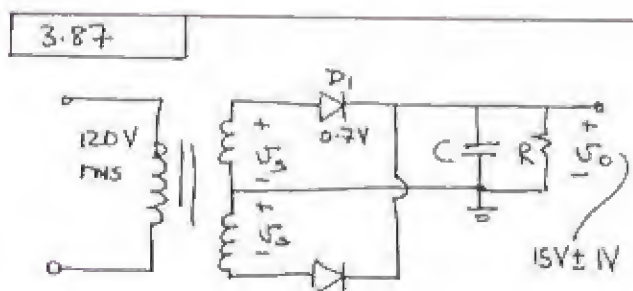
$$(d) \quad i_{D, avg} = I_L \left(1 + \pi \sqrt{\frac{2(V_p - V_{D0})}{V_r}} \right)$$

$$\text{using } I_L = \frac{V_{D0, avg}}{R} = \frac{15}{R} \quad \text{we have}$$

$$i_{D, avg} = \frac{15}{150} \left(1 + \pi \sqrt{\frac{2(16)}{2}} \right) \\ = \underline{1.36A}$$

$$(e) \quad i_{D, peak} = I_L \left(1 + 2\pi \sqrt{\frac{2(V_p - V_{D0})}{V_r}} \right)$$

$$= \frac{15}{150} \left(1 + 2\pi \sqrt{\frac{2(16)}{2}} \right) \\ = \underline{2.61A}$$



$$(a) \quad \hat{V}_0 = 16V$$

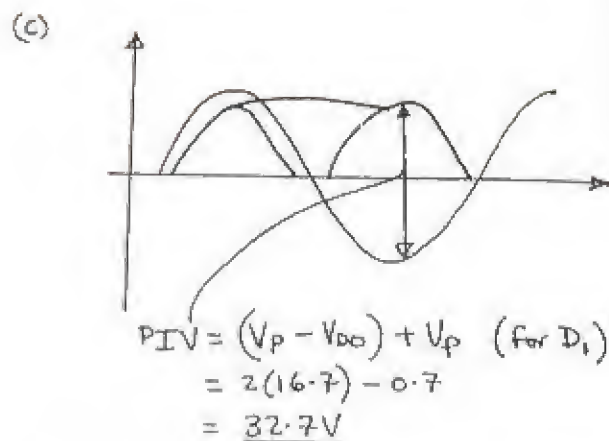
$$\therefore \hat{V}_S = 16 + V_{D0} = 16.7V$$

$$\text{RMS Voltage across secondary} \\ = \frac{2 \times 16.7}{\sqrt{2}} \\ = \underline{23.6V}$$

$$(b) \quad \text{Using } E_q. (3.28)$$

$$V_r = \frac{V_p}{2fCR} = \frac{16}{2 \times 60 \times C \times 150} = 2$$

$$C = \underline{444.4 \mu F}$$



$$\therefore \text{Using a 50\% margin}$$

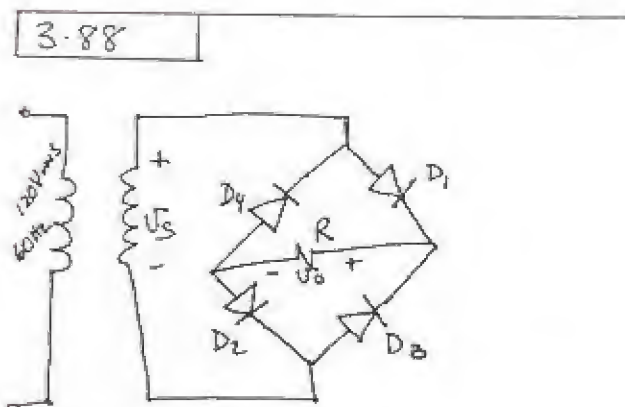
$$PIV = 1.5(32.7) = \underline{49V}$$

$$(d) \quad \text{Using } E_q. (3.34)$$

$$i_{D, avg} = I_L \left(1 + \pi \sqrt{\frac{V_p/2}{V_r}} \right) \\ = \frac{15}{150} \left(1 + \pi \sqrt{\frac{16}{2 \times 2}} \right) \\ = \underline{0.73A}$$

$$(e) \quad \text{Using } E_q. (3.35)$$

$$i_{D, max} = I_L \left(1 + 2\pi \sqrt{\frac{V_p/2}{V_r}} \right) \\ = \frac{15}{150} \left(1 + 2\pi \sqrt{\frac{16}{2 \times 2}} \right) \\ = \underline{1.36A}$$



$$V_0 = 15 \pm 1V, R = 150\Omega$$

CONT.

$$\hat{V}_0 = 16V$$

$$\hat{V}_3 = 16 + 2V_{D0} = 17.4V$$

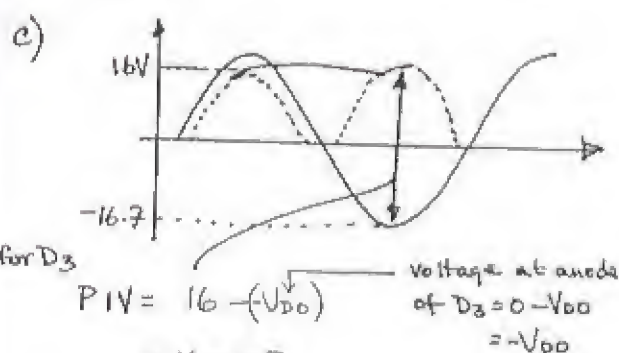
$$\text{RMS Secondary Voltage} = \frac{17.4}{\sqrt{2}} = \underline{12.3V}$$

$$(b) V_r = \frac{V_p}{2fCR}$$

$$Z = \frac{16}{2 \times 60 \times C \times 50}$$

$$C = \underline{444.4 \mu F}$$

note: we got the same value for C as the full wave rectifier as discharge is over the same amt of time $T/2$ and the peak is the same - 16V.



Allowing a 50% margin = 16.7×1.5
 $= \underline{25V}$

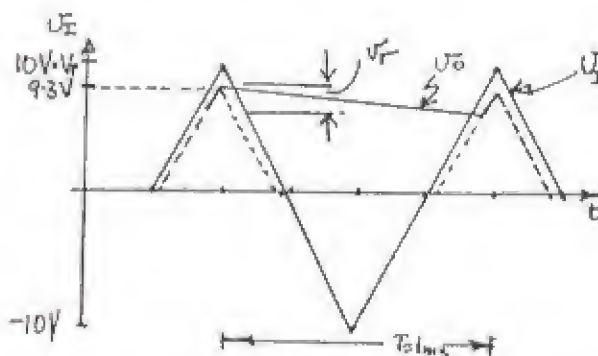
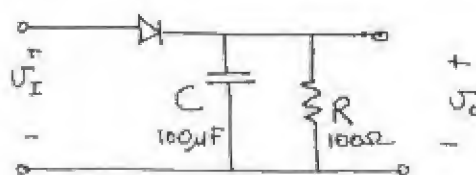
(d) Using 3.34

$$\begin{aligned} I_{D,avg} &= I_L \left(1 + \pi \sqrt{V_p / 2V_r} \right) \\ &= \frac{15}{150} \left(1 + \pi \sqrt{16 / 2 \times 2} \right) \\ &= \underline{0.73A} \end{aligned}$$

(e) Using (3.35)

$$\begin{aligned} I_{D,max} &= I_L \left(1 + 2\pi \sqrt{V_p / 2V_r} \right) \\ &= \frac{15}{150} \left(1 + 2\pi \sqrt{16 / 2 \times 2} \right) \\ &= \underline{1.36A} \end{aligned}$$

3.89



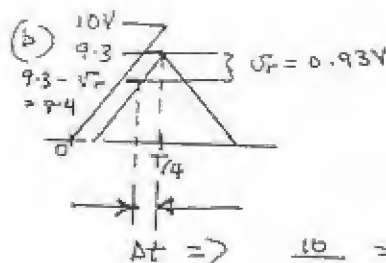
During the diode is off interval, the capacitor discharges through the resistor R according to:

$$V_0 = 9.3 e^{-t/RC} \approx 9.3(1 - T/CR)$$

$$\begin{aligned} \infty V_r &= 9.3 - 9.3(1 - T/CR) \\ &= 9.3T/CR \\ &= \frac{9.3}{fCR} \\ &= 0.93V \end{aligned}$$

NB this is $E_8(3.38)$

$$\begin{aligned} V_{0,avg} &= V_0 - V_{D0} - \frac{1}{2} V_r \\ &= 9.3 - \frac{1}{2} 0.93 \\ &= \underline{8.84V} \end{aligned}$$



$$\Delta t \Rightarrow \frac{10}{T_4} = \frac{0.93}{\Delta t}$$

$$\Delta t = 0.02325T$$

$$= \underline{0.02325 ms}$$

CONT.

(c) \therefore Charge gained during conduction = Charge lost during discharge

$$i_{C,avg} \Delta t = C V_r$$

$$i_{C,avg} = \frac{C V_r}{\Delta t} = \frac{100 \times 10^{-6} \times 0.93}{0.02325 \times 10^{-3}}$$

$$= 4.0 \text{ A}$$

$$i_{D,avg} \cong i_{C,avg} + i_{L,avg} \quad \leftarrow \frac{V_{D,avg}}{R}$$

$$\cong 4.0 + \frac{8.84}{100} = \underline{\underline{4.09 \text{ A}}}$$

$$(d) \quad i_{C,max} = C \left. \frac{\delta V_D}{\delta t} \right|_{\text{at onset of conduction}}$$

$$= C \frac{\delta V_r}{\delta t}$$

$$= 100 \times 10^{-6} \times 40 \times 10^3$$

$$= \underline{\underline{4 \text{ A}}}$$

$$i_{D,max} = i_{C,max} + i_{L,max}$$

$$= 4 + V_{D,max}/100$$

$$= 4 + 9.3/100$$

$$= 4.09 \text{ A}$$

Note that in this case $i_{D,avg} = i_{D,max}$ owing to the linear input (i_C is constant and i_L is approximately constant).

3.90

Refer to Fig P3.82 and let capacitor C be connected across each of the load resistors R . The two supplies, V_D^+ and V_D^- are identical. Each is a full-wave rectifier similar to that based on the centre-tapped transformer circuit. For each supply, the dc output is 15V and the ripple is 1V peak-to-peak. Thus $V_D = 15 \pm 0.5 \text{ V}$. It follows that the peak value of V_S must be $15.5 + 0.7 = 16.2 \text{ V}$.
 \therefore Voltage across secondary = $2(16.2)$
 $= 32.4 \text{ V}$

$$\text{RMS across secondary} = \frac{32.4}{\sqrt{2}} = \underline{\underline{22.9 \text{ V}_{rms}}}$$

$$\text{Turns Ratio} = \frac{120}{22.9} = 5.24:1$$

Use Eq. (3.35) to find

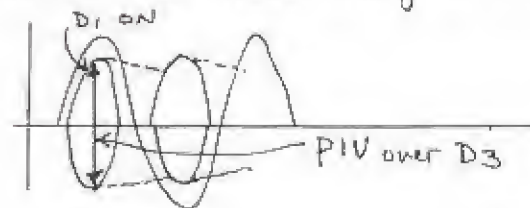
$$i_{D,max} = I_L \left(1 + 2\pi \sqrt{\frac{V_D/2V_r}{}} \right) \\ = 0.2 \left(1 + 2\pi \sqrt{\frac{15.5/2}{}} \right) \\ = \underline{\underline{3.70 \text{ A}}}$$

$$V_r = \frac{V_D}{2fCR} = 1 \quad \text{Eq. (3.28)}$$

DISCHARGE OCCURS OVER $T/2 = \frac{1}{2f}$

$$\Rightarrow C = \frac{15.5}{2 \times 60 \times 75} \quad \text{where } 200 \text{ mA} = \frac{15}{R} \\ R = \frac{15}{0.2} = 75 \Omega \\ = \underline{\underline{1722 \mu\text{F}}}$$

Consider D_3 when looking at PIV



CONT.

$$PIV = \hat{V}_O + \hat{V}_S \\ = 15.5 + 16.2 = 31.7V$$

Allowing for 50% safety margin

$$PIV = 1.5 \times 31.7 = \underline{47.6V}$$

Use Eq (3.34) to find

$$\hat{I}_{D,avg} = I_L \left(1 + \pi \sqrt{V_F / 2V_r} \right) \\ = 0.2 \left(1 + \pi \sqrt{15.5/2} \right) \\ = \underline{1.95A}$$

3.91

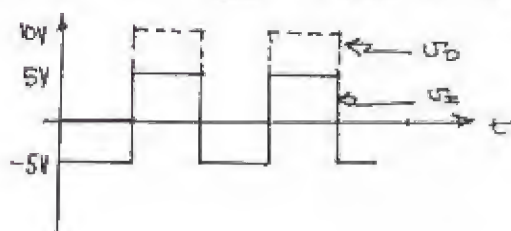
$$V_O = V_E (1 + R/R) \\ = 2V_E \text{ when the diode is conducting.}$$

$$(a) V_E = +1V \quad V_O = 2V \quad V_A = 1.7V \quad V_- = V_E = 1V$$

$$b) V_E = 2V \quad V_O = 4V \quad V_A = 4.7V \quad V_- = 2V$$

$$c) V_E = -1V \quad V_A = -1.7V \sim \text{diode is cut off} \\ V_O = 0V \\ V_- = 0V$$

$$d) V_E = -2V \quad V_A = -1.7V \quad V_O = 0V \quad V_- = 0V$$



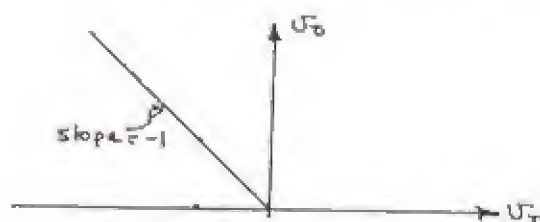
$$V_{O,avg} = \underline{5V}$$

3.92

$V_E > 0$ D_1 conducts D_2 cut off

$V_E < 0$ D_1 cut off

D_2 conducts $\sim \frac{V_O}{V_E} = -1$



$$a) V_E = 1V \quad V_O = 0V$$

$V_A = -0.7V$ - keeps D_2 off so no current flows through R

$\Rightarrow V_- = 0V$ - virtual gnd as R is closed through D_1

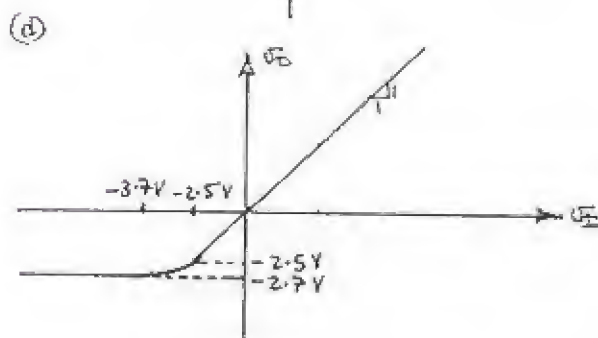
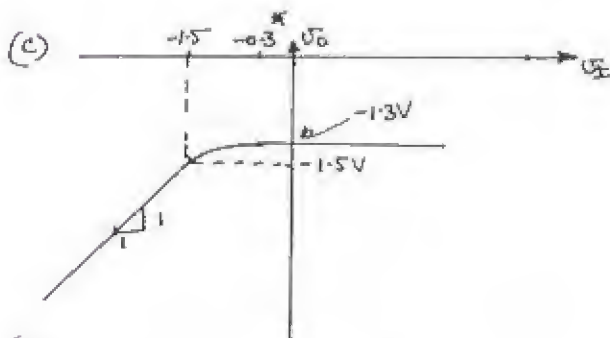
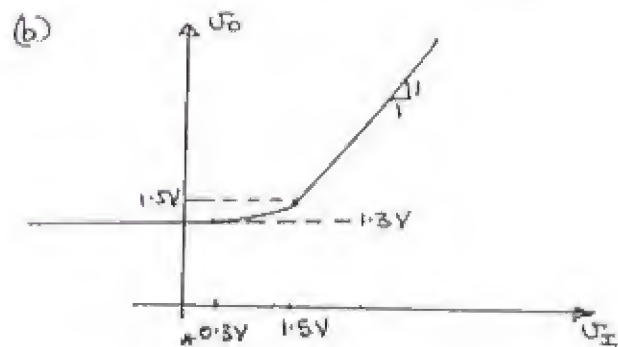
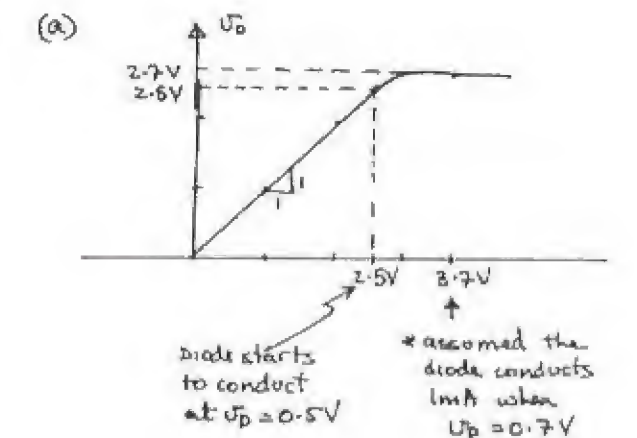
$$(b) V_E = 2V \\ V_O = 0V \\ V_A = -0.7V \\ V_- = 0V$$

$$(c) V_E = -1V \\ V_O = 1V \\ V_A = 1.7V \\ V_- = 0V$$

\sim virtual gnd as negative feedback is closed through R .

$$(d) V_E = -2V \Rightarrow V_O = 2V \\ V_A = 2.7V \\ V_- = 0V$$

3.93	
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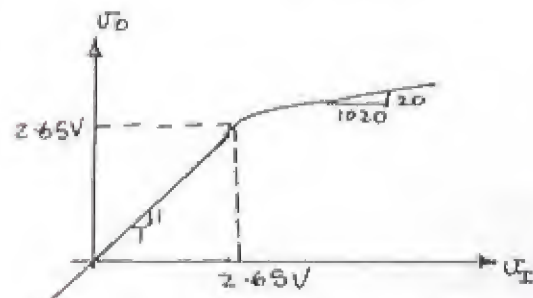
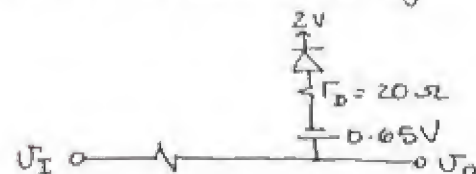


3.94	
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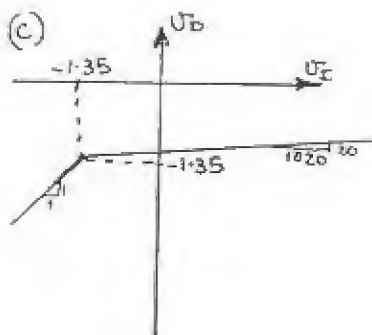
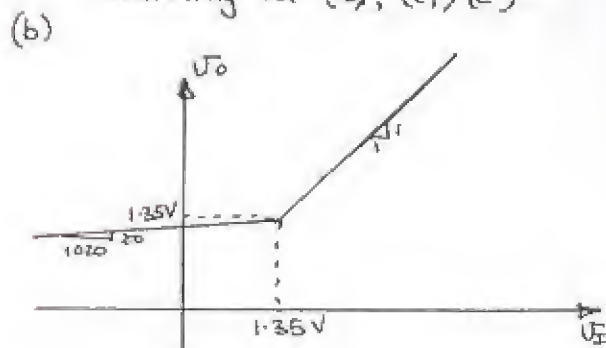
(a) $V_E < 2.65V$ ~ the diode is off
and the circuit reduces to:

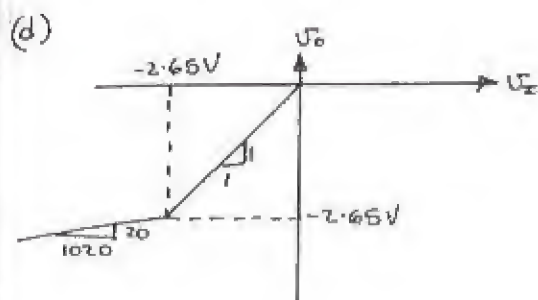


With the diode conducting we have:

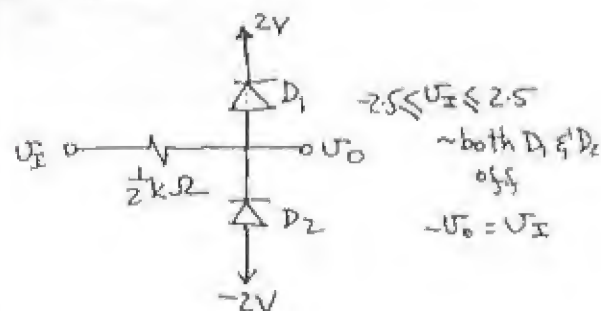


Similarly for (b), (c), (d)

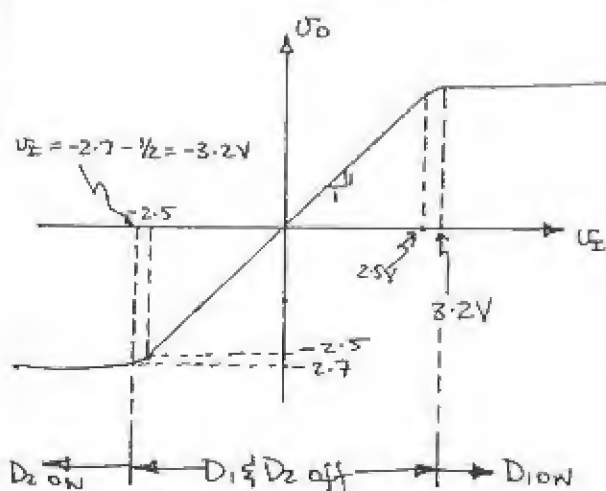




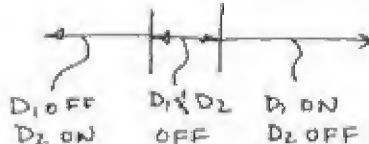
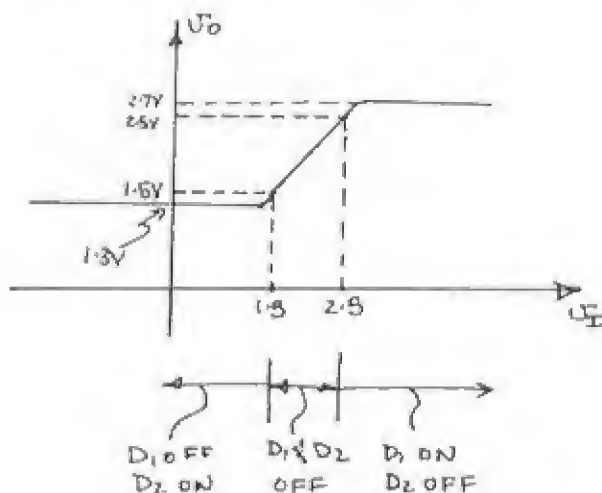
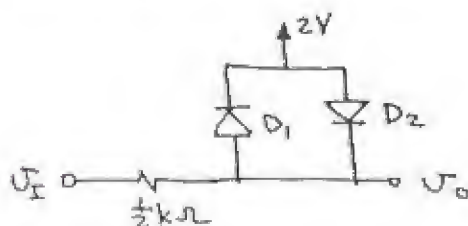
3.95



For $U_I \geq 2.5V$ $\sim D_1$ on
 $U_{D1} = 0.7$ at $i_{D1} \geq 1mA$
 $U_o = 2.7V$ at $U_I = 2.7 + \frac{1}{2} \times 1$
 $= \underline{\underline{3.2V}}$



3.96



3.97

For each diode



For the Zener diode



$$8.2 = V_{z0} + 10 \times 10^{-3} \times 20$$

$$V_{z0} = 8.0V$$

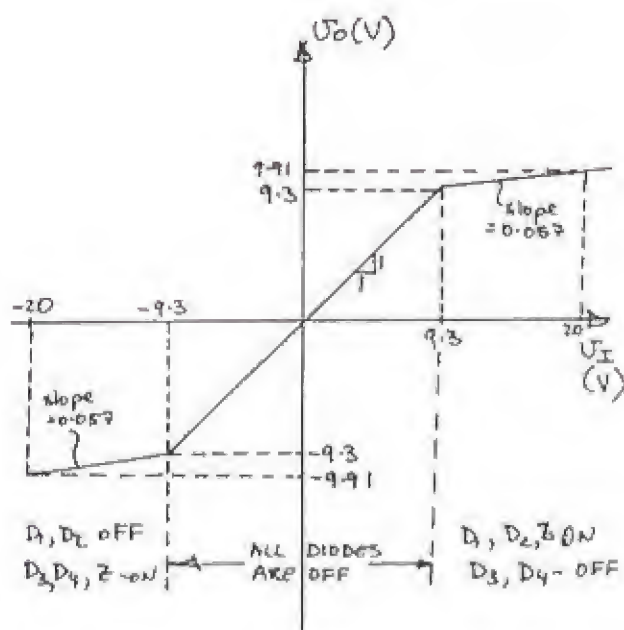
The limiter thresholds are

$$\pm (2 \times 0.65 + 8.0) = \pm 9.3V$$

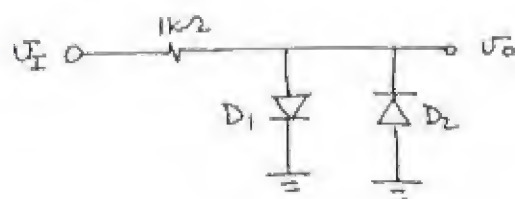
For $U_I > 9.3$ (as well as for $U_I < -9.3$)

$$\frac{\partial U_o}{\partial U_I} = \frac{r_{D1} + r_z + r_{D2}}{1k\Omega + r_{D1} + r_z + r_{D2}} = \frac{3(20)}{1k\Omega + 3(20)} = 0.057 \frac{V}{V}$$

CONT.



3.98



for D_1

Given $\frac{i_D}{1\text{mA}} = e^{\frac{V_D - 0.7}{nV_T}}$

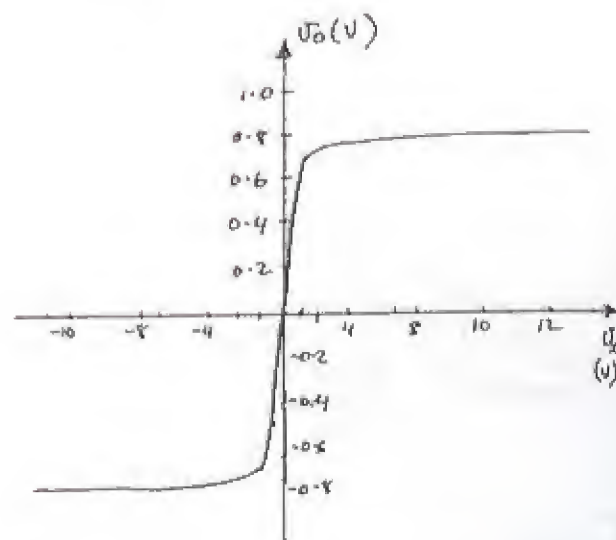
$$(V_D - 0.7) = nV_T \ln\left(\frac{i_D}{1\text{mA}}\right) = 0.1 \log\left(\frac{i_D}{10^{-3}}\right) \leftarrow \text{can find } V_D \text{ from } i_D$$

$$\therefore i_D = 10^{-3} \times 10^{\frac{V_D - 0.7}{0.1}} = 10^{-3} \times 10^{10(V_D - 0.7)}$$

$$\text{KVL } V_I = V_D + i_D \times 10^3 = V_D + 10^{10(V_D - 0.7)}$$

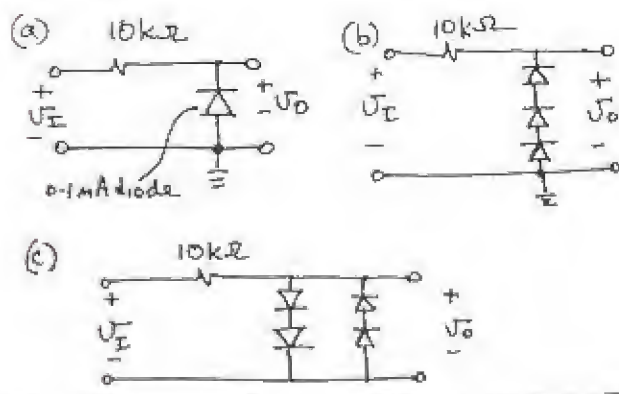
for D_2 : $V_I = V_D - 10^{10(V_D - 0.7)}$

$V_O (V)$	$V_I (V)$	
0.5	0.510	} D_1 ON
0.6	0.7	
0.7	1.7	
0.8	10.7	
0	0	} D_2 ON
-0.5	-0.51	
-0.6	-0.7	
-0.7	-1.7	
-0.8	-10.7	

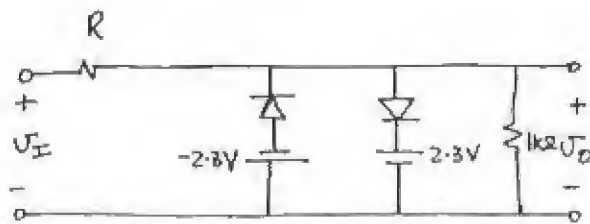


The limiter is fairly hard with a gain $K \approx 1$
 $L_+ \approx \underline{0.8V}$, $L_- \approx \underline{-0.8V}$

3.99



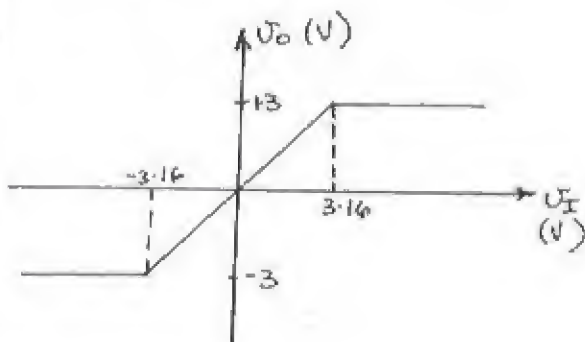
3.100



In the limiting region

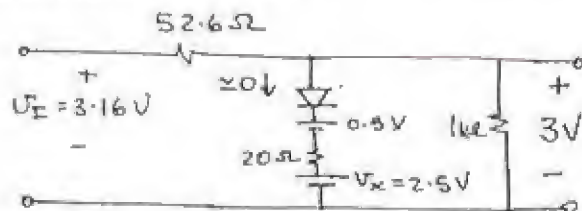
$$\frac{V_O}{V_I} = \frac{1000}{1000 + R} \geq 0.95$$

$$R \leq \underline{52.6 \Omega}$$



$$\frac{0.2}{10 \times 10^3} = 20 \Omega \sim$$

At the verge of limiting in the positive direction we have :-



For $V_I = 10V$

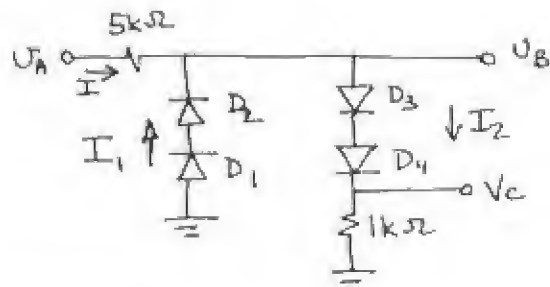
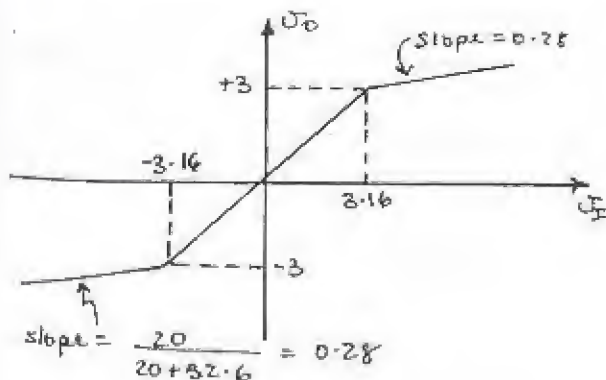
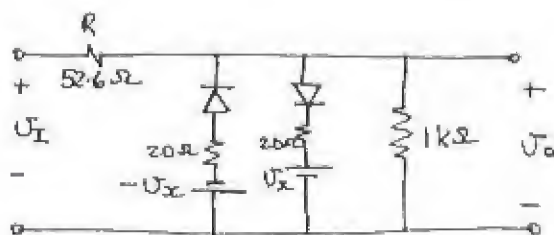
$$V_O \approx 3 + 0.28(10 - 3.16) = \underline{4.9V}$$

For $V_I = -10V$

$$V_O = \underline{-4.9V}$$

3.102

3.101



$$V_O = 0.7 + 0.1 \log(10/0.1)$$

(a) For $V_A > 0$ D_1, D_2 off $\Rightarrow I_1 = 0$

$$I = I_2 = V_O / 1k\Omega \quad V_A = V_O + I \cdot 5$$

(b) For $V_I < 0$ D_3, D_4 off $\Rightarrow V_C = 0$

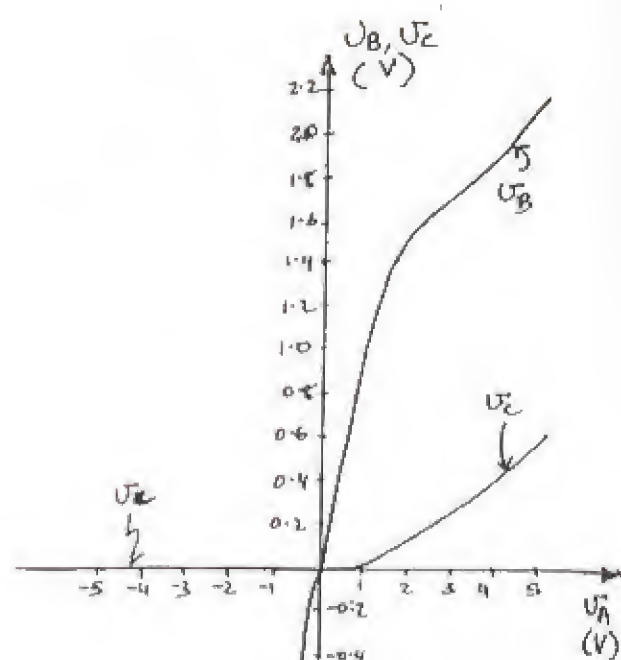
$$I = -I_1 \quad V_B = -(V_{D1} + V_{D2})$$

$$V_A = -(V_B + 5I_1)$$

CONT.

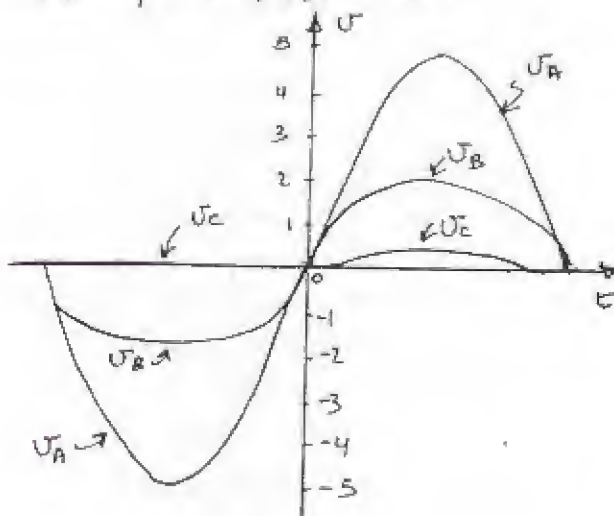
(a) List of points for $V_A > 0$

V_E (V)	I_E (mA)	V_{D3}, V_{D4} (V)	$V_B = V_E + V_{D3} + V_{D4}$ (V)	V_A (V)
0.0001	0.0001	0.4	0.8	0.8
0.001	0.001	0.5	1.00	1.01
0.01	0.1	0.6	1.21	1.24
0.1	0.1	0.7	1.50	1.90
0.2	0.2	0.73	1.66	2.66
0.3	0.3	0.75	1.80	3.30
0.4	0.4	0.76	1.92	3.92
0.5	0.5	0.77	2.04	4.54
0.6	0.6	0.78	2.16	5.16

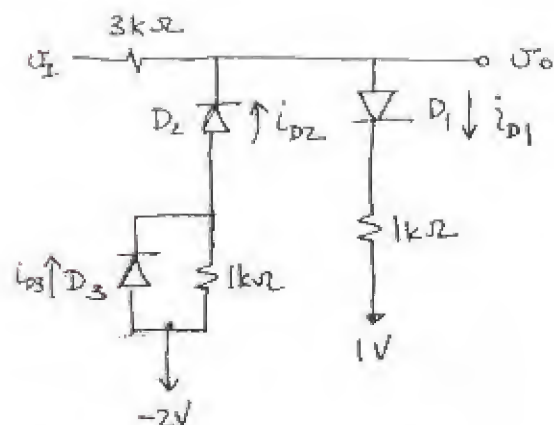


(b) List of Points for $V_A < 0$

I_1 (mA)	V_{D1}, V_{D2} (V)	V_B (V)	V_A (V)
0.0001	0.4	-0.80	-0.80
0.001	0.5	-1.00	-1.01
0.01	0.6	-1.20	-1.25
0.10	0.7	-1.40	-1.90
0.20	0.73	-1.46	-2.46
0.30	0.75	-1.50	-3.00
0.40	0.76	-1.52	-3.52
0.50	0.77	-1.54	-4.04
0.60	0.78	-1.56	-4.56
0.70	0.785	-1.57	-5.07



3.103



At currents $i_{D1} > 1 \text{ mA}$, $V_{D1} \approx 0.7 \text{ V}$
 Let $V_{D1} = 0.71 \text{ V}$ $V_E > 5.7 \text{ V}$

CONT.

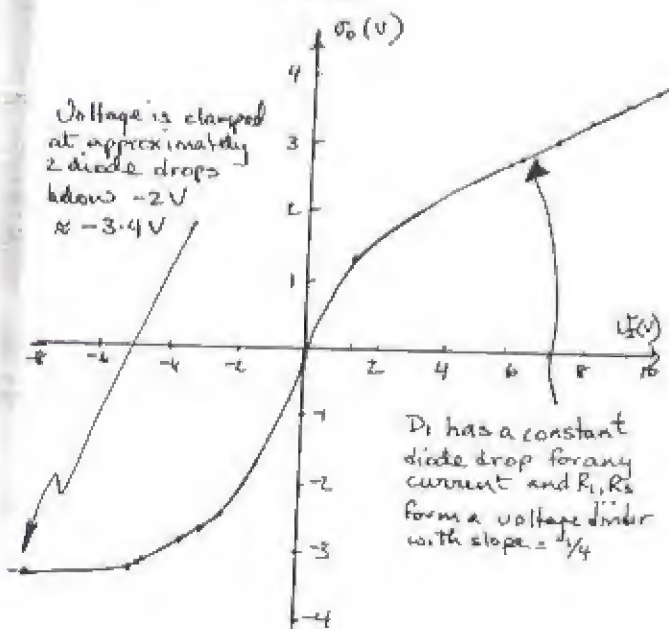
$$V_o = 1.71 + i_{D1} \times 1k\Omega$$

$$= 1.71 + \left(\frac{V_E - 1.71}{4} \right) \times 1$$

$$= \frac{V_E}{4} + 1.2825 \quad \text{HB slope} = 1/4$$

∴ For $V_E > 5V$ slope $V_o/V_E \approx 1/4$

$V_E (V)$	$V_o (V)$
5.8	2.7325
6.0	2.7825
7.0	3.0325
8.0	3.2825
9.0	3.5325
10.0	3.7825



where points for $-8 \leq V_E \leq 6V$ are calculated as shown below:

$$I_D = 1mA \text{ at } V_D = 0.7V \quad n=1$$

$$I_D = I_S e^{0.7/0.025} = 10^{-3}$$

$$I_S = 6.914 \times 10^{-16} A$$

∴ For Diodes use $I_D = 6.914 \times 10^{-16} e^{V_D/0.025}$

D_1 conducting $i_{D2} = 0$

i_{D1} (A)	V_{D1} (V)	V_o (V)	$V_E = (4k)i_{D1} + V_{D1} + 1$ (V)
10^{-6}	0.297	1.297	1.297
10^{-4}	0.527	1.528	1.5313
10^{-5}	0.584	1.595	1.625
10^{-4}	0.64	1.742	2.042
10^{-3}	0.70	2.7	5.7
0.2×10^{-2}	0.74	6.74	12.74
10^{-2}	0.758	11.75	41.75

even at small i_{D1} , $V_o > 1V$, $V_o \approx V_E$ since $i_{D1} \approx 0$

For the D_2, D_3 arm conducting use the following equations:

Note $V_E < -2.5V$

Starting with a value for V_A we have

$$V_{D3} = V_A + 2 \quad V_{D3}/0.025 \quad (2)$$

$$i_{D3} = I_S e$$

$$i_{D2} = i_{D3} + \frac{V_A + 2}{1} \quad (3)$$

$$V_{D2} = 0.025 \ln \left(\frac{i_{D2}}{6.914 \times 10^{-16}} \right) \quad (4)$$

$$V_o = V_A - V_{D2} \quad (5)$$

$$V_E = V_o - i_{D2} \times 3k\Omega \quad (6)$$

① V_A (V)	② i_{D3} (A)	③ i_{D2} (A)	④ V_{D2} (V)	⑤ V_o (V)	⑥ V_E (V)
-2.001	7×10^{-16}	10^{-6}	0.527	-2.528	-2.531 (A)
-2.01	10^{-15}	10^{-5}	0.585	-2.595	-2.625
-2.10	3.8×10^{-14}	10^{-4}	0.642	-2.724	-3.024
-2.20	2×10^{-12}	0.2×10^{-3}	0.659	-2.859	-3.459
-2.5	$33 \mu A$	0.5×10^{-3}	0.682	-3.128	-4.628 (B)
-2.6	$18 \mu A$	0.4×10^{-3}	0.687	-3.287	-5.087
-2.7	$1mA$	1.7×10^{-3}	0.713	-3.413	-8.516 (C)
-2.71	$1.5 \mu A$	$2.2 \mu A$	0.720	-3.43	-10

(A) for small i_{D2} , D_3 is off and D_2 is on
∴ i_{D2} flows through $1k\Omega$ resistor

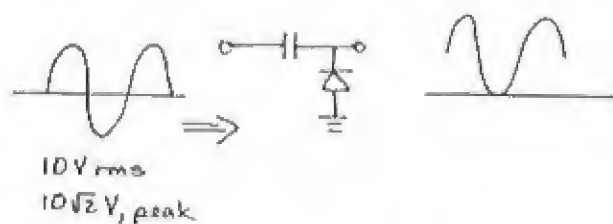
CONT.

(B) 0.5 V drop across D_3 causes D_3 to start to conduct

(C) $V_A = -2.7V$

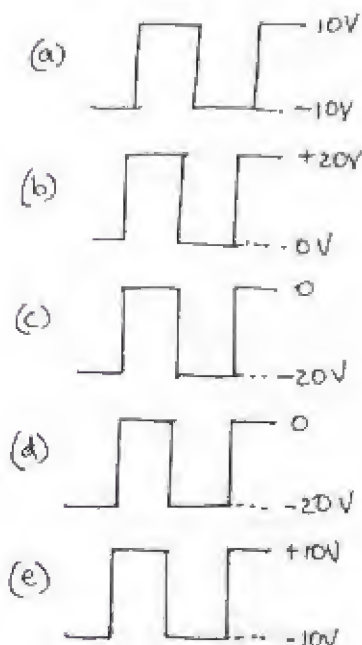
The 0.7 voltage across D_3 clamps the voltage across R_3 so that D_3 control the current I_{O2}

3.104



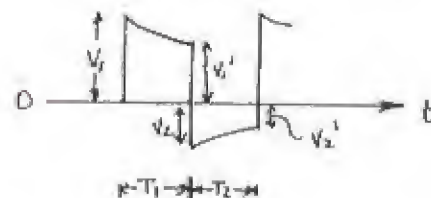
Average (dc) value of output = $10\sqrt{2}$
= 14.14 V

3.105



(f) Here there are two different time constants involved. To calculate the output levels we shall exaggerate the discharge and charge waveforms.

During T_1 $V_0 = V_1 e^{-t/RC}$
At $t = T_1 = T$ $V_0 = V_1'$
= $V_1 e^{-T/RC}$



where for $T \ll CR$

$V_1' \approx V_1 (1 - T/CR) = V_1 (1 - \alpha)$ where $\alpha \ll 1$

During the period T_2

$|V_0| = |V_2| e^{-t/CR/2}$

at the end of T_2 $t = T$, $V_0 = V_2'$

where $V_2' = |V_2| e^{-T/CR/2}$

$\approx |V_2| (1 - \frac{T}{CR/2}) = |V_2| (1 - 2\alpha)$

Now $V_1' + |V_2| = 20 \Rightarrow V_1 + |V_2| - 2\alpha V_1 = 20$ ①

and $|V_2'| + V_1 = 20 \Rightarrow V_1 + |V_2| - 2\alpha |V_2| = 20$ ②

from ① & ② we find that

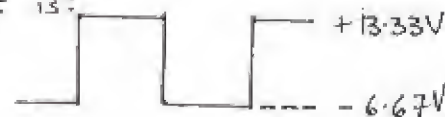
$V_1 = 2V_2$

Then using ① and neglecting αV_1 yields

$3|V_2| = 20 \Rightarrow |V_2| = \underline{6.67V}$

$V_1 = \underline{13.33V}$

The result is:



CONT.



(h) Using a method similar to that employed for case (f) above we obtain.



3.106

$$n_i^2 = BT^3 e^{-E_g/kT}$$

$$B = 5.4 \times 10^{31}$$

$$E_g = 1.12 \text{ eV for silicon}$$

$$k = 8.62 \times 10^{-5} \frac{\text{eV}}{\text{K}}$$

Fraction of ionized atoms = $n_i / 5 \times 10^{22}$; $T = 273 + x^\circ\text{C}$

T (K)	n_i (carriers/cm ³)	Fraction of ionized atoms.
263	2.68×10^5	5.37×10^{-18}
273	1.53×10^9	3.07×10^{-14}
293	8.65×10^9	1.73×10^{-13}
373	1.44×10^{12}	2.89×10^{-11}
398	4.75×10^{12}	9.51×10^{-11}

3.107

(a) intrinsic silicon

$$\rho = \frac{1}{q(P\mu_p + n\mu_n)}$$

$$= \frac{1}{1.6 \times 10^{-19} (1.5 \times 10^{10} \times 480 + 1.5 \times 10^{10} \times 1350)}$$

$$= 2.28 \times 10^5 \Omega \cdot \text{cm}$$

$$R = \rho L/A = 2.28 \times 10^5 \frac{10 \times 10^{-4}}{3.4 \times 10^{-4}} = 7.6 \times 10^4 \Omega$$

(b)

$$\rho = \frac{1}{q(P\mu_p + n\mu_n)}$$

$$= \frac{1}{(1.6 \times 10^{-19}) \left(\frac{(1.5 \times 10^{10})^2}{10^{16}} \times \frac{1200}{2.5} + 10^{16} \times 1200 \right)}$$

$$= 0.521 \Omega \cdot \text{cm}$$

$$R = \rho \times 10^3 / 3 = 1.74 \text{ k}\Omega$$

(c) n doped $N_D = N_{A0} = 10^{18}$

$$n_{p0} = n_i^2 / N_{A0}$$

$$\rho = \frac{1}{1.6 \times 10^{-19} \left(\frac{(1.5 \times 10^{10})^2}{10^{18}} \times \frac{1100}{2.5} + 10^{18} \times 1200 \right)}$$

$$= 5.21 \times 10^{-3} \Omega \cdot \text{cm}$$

$$R = \rho \frac{10^3}{3} = 17.4 \Omega$$

(d) P doped $N_A = P_{A0} = 10^{10} / \text{cm}^3$

$$\rho = \frac{1}{q(P\mu_p + n\mu_n)}$$

$$= \frac{1}{1.6 \times 10^{-19} \left(\frac{10^{10} \times 1200}{2.5} + \frac{(1.5 \times 10^{10})^2}{10^{10}} \times 1200 \right)}$$

$$= 2.05 \times 10^4 \Omega \cdot \text{cm}$$

$$R = \rho \frac{10^3}{3} = 68.35 \text{ k}\Omega$$

$$(e) R = 2.8 \times 10^4 / 3 = 0.933 \Omega$$

3.108

$$\rho_{n0} = \frac{n_i^2}{N_D} = \frac{(1.5 \times 10^{10})^2}{10^{16}} = 2.25 \times 10^4 / \text{cm}^3$$

CONT.

$$\frac{dP}{dx} = \frac{1000 P_{A0} - P_{A0}}{W}$$

$$\approx \frac{2.25 \times 10^{-1}}{5 \times 10^{-4}}$$

$$J_p = -q D_p \frac{dP}{dx}$$

$$= -1.6 \times 10^{-19} \times 12 \times \frac{-2.25 \times 10^{-1}}{5 \times 10^{-4}}$$

$$= \underline{\underline{8.64 \times 10^{-8} \text{ A/cm}^2}}$$

3.109

$$v_{drift,p} = \mu_p E$$

$$= 480 \frac{\text{cm}^2}{\text{V}\cdot\text{s}} \times \frac{1}{10^3} \frac{\text{V}}{\text{cm}}$$

$$= \underline{\underline{4.8 \times 10^5 \text{ cm/s}}}$$

$$v_{drift,n} = \mu_n E$$

$$= 1350 \frac{\text{cm}^2}{\text{V}\cdot\text{s}} \times \frac{1}{10^3} \frac{\text{V}}{\text{cm}}$$

$$= \underline{\underline{135 \times 10^5 \text{ cm/s}}}$$

3.110

$$J_{drift} = q (n \mu_n + p \mu_p) E \quad \text{A/cm}^2$$

$$I_{drift} = q (n \mu_n + p \mu_p) E \cdot A$$

$$= 1.6 \times 10^{-19} (10^5 \cdot 1350 + 10^{15} \cdot 480) \times \frac{1}{10^2} \times (5 \times 10^{-8})$$

$$= \underline{\underline{15.36 \mu\text{A}}}$$

3.111

$$E = \frac{1 \text{ V}}{10 \times 10^{-4}} = \frac{1}{10^{-3}} \frac{\text{V}}{\text{cm}}$$

$$n_{A0} = N_D \quad P_{A0} = \frac{n_i^2}{N_D} \quad \text{assume } P_{A0} \ll n_{A0}$$

$$\therefore J_{drift} = q (\mu_n n + \mu_p p) E = \frac{10^{-5}}{10^{-3}} \frac{\text{A}}{\text{cm}^2}$$

$$\approx 1.6 \times 10^{-19} (1350 N_D) \frac{1}{10^{-3}} = 10^5$$

$$N_D = 4.6 \times 10^{17} / \text{cm}^3$$

3.112

$$P_{D0} = N_A = 10^{16} / \text{cm}^3 \quad \text{at all temperatures}$$

$$\text{At } 25^\circ\text{C} \approx 300\text{K}$$

$$n_i^2 = B T^3 e^{-E_g / kT}$$

$$= 5.4 \times 10^{31} (300)^3 e^{-1.12 / (8.62 \times 10^{-5} (300))}$$

$$= 2.26 \times 10^{20}$$

$$n_{D0} = \frac{n_i^2}{N_A} = \underline{\underline{2.26 \times 10^4 / \text{cm}^3}}$$

$$\text{At } 125^\circ\text{C} \approx 400\text{K}$$

$$n_i^2 = 5.4 \times 10^{31} (400)^3 e^{-1.12 / (8.62 \times 10^{-5} (400))}$$

$$= 2.7 \times 10^{25}$$

$$n_{D0} = \frac{n_i^2}{N_A} = \underline{\underline{2.7 \times 10^9 / \text{cm}^3}}$$

3.113

DOPING CONCENTRATION	μ_n $\text{cm}^2/\text{V}\cdot\text{s}$	μ_p $\text{cm}^2/\text{V}\cdot\text{s}$	D_n cm^2/s	D_p cm^2/s
INTRINSIC	1350	480	34	12
10^{16}	1100	400	28	10
10^{17}	700	260	18	6
10^{18}	360	150	9	4

where $D_n = V_T \mu_n = \underline{0.025 \mu m}$

$D_p = V_T \mu_p = \underline{0.025 \mu m}$

3.114

$$V_0 = V_T \ln \left(\frac{N_A N_D}{n_i^2} \right) = 0.025 \ln \left(\frac{10^{16} 10^{16}}{10^{10}} \right)$$

$$= 1.27 \text{ V}$$

$$W_{dep} = x_n + x_p = \sqrt{\frac{2\epsilon_s}{q} \left(\frac{1}{N_A} + \frac{1}{N_D} \right) V_0}$$

$$= \sqrt{\frac{2(11.7) 8.85 \times 10^{-14}}{1.6 \times 10^{-19}} \left(\frac{1}{10^{16}} + \frac{1}{10^{16}} \right) 1.27}$$

$$= 57 \times 10^{-6} \text{ cm}$$

$$= \underline{0.57 \mu m}$$

$$\frac{x_n}{x_p} = \frac{\mu_n}{\mu_p} \Rightarrow x_n = x_p = \underline{0.28 \mu m}$$

$$q_J = q_N = q_P = q \frac{N_A N_D}{N_A + N_D} A W_{dep}$$

$$= \underline{45.6 \times 10^{-15} \text{ C}}$$

$$C_j = \frac{\epsilon_s A}{W_{dep}} = \frac{11.7 (8.85 \times 10^{-14}) \times 100 \times 10^{-8}}{0.57 \times 10^{-4}}$$

$$= \underline{18.2 \text{ fF}}$$

3.115

$$V_0 = V_T \ln \left(\frac{N_A N_D}{n_i^2} \right) = 0.025 \ln \left(\frac{10^{16} 10^{15}}{10^{20}} \right)$$

$$= 0.633 \text{ V}$$

$$W_{dep} = x_n + x_p = \sqrt{\frac{2\epsilon_s}{q} \left(\frac{1}{N_A} + \frac{1}{N_D} \right) (V_0 + V_R)}$$

$$W_{dep} = \sqrt{\frac{2(11.7)(8.85 \times 10^{-14})}{1.6 \times 10^{-19}} \left(\frac{1}{10^{16}} + \frac{1}{10^{15}} \right) (0.633 + 5)}$$

$$= 2.83 \times 10^{-4} \text{ cm} = \underline{2.83 \mu m}$$

$$x_n = \frac{N_A}{N_D} x_p = 10 x_p$$

$$\therefore x_p = \frac{2.83}{11} = \underline{0.26 \mu m}$$

$$x_n = \underline{2.57 \mu m}$$

$$q_J = q_N = q_P = q \frac{N_A N_D}{N_A + N_D} A W_{dep}$$

$$= 1.6 \times 10^{-19} \left(\frac{10^{16} 10^{15}}{10^{16} + 10^{15}} \right) 400 \times 10^{-8} \times 2.83 \times 10^{-4}$$

$$= \underline{1.65 \times 10^{-13} \text{ C}}$$

$$C_j = \frac{\epsilon_s A}{W_{dep}} = \frac{11.7 (8.85 \times 10^{-14}) 400 \times 10^{-8}}{2.83 \times 10^{-4}}$$

$$= 14.6 \times 10^{-15} = \underline{14.6 \text{ fF}}$$

3.116

$$q_J = q_N \times A = 1.6 \times 10^{-19} \times 10^{16} \times 0.1 \times 10^{-4} \times 100 \times 10^{-8}$$

$$= \underline{16 \text{ fC}}$$

3.117

$$q_J = q \frac{N_A N_D}{N_A + N_D} A W_{dep}$$

$$= q \frac{N_A N_D}{N_A + N_D} A \sqrt{\frac{2\epsilon_s}{q} \left(\frac{1}{N_A} + \frac{1}{N_D} \right) (V_0 + V_R)}$$

CONT.

$$\frac{d q_b}{d V_R} = \frac{q N_A N_D}{N_A + N_D} A \frac{1}{\sqrt{\frac{2 \epsilon_s}{q} \left(\frac{1}{N_A} + \frac{1}{N_D} \right) (V_0 + V_R)}} \times \frac{q \epsilon_s}{q} \left(\frac{1}{N_A} + \frac{1}{N_D} \right)$$

$$= \frac{\epsilon_s A}{W_{dep}}$$

3.118

$$C_j = \frac{C_{j0}}{(1 + V_R/V_0)^m}$$

$$V_R = 1V \quad C_j = \frac{0.6 \text{ pF}}{(1 + 1/0.75)^{1/3}} = \underline{0.45 \text{ pF}}$$

$$V_R = 10V \quad C_j = \frac{0.6 \text{ pF}}{(1 + 10/0.75)^{1/3}} = \underline{0.25 \text{ pF}}$$

3.119

$$V_Z = 10$$

$$I_D = \frac{1}{2} \left(\frac{0.25}{10} \right) = \underline{12.5 \text{ mA}}$$

Since breakdown occurs only half the time, the average breakdown current can be twice the continuous value i.e. it can be 25 mA if the dissipation is limited to half the rated value of 50 mW if the dissipation is allowed to rise to the rated value.

3.120

$$I_P = A q n_i^2 \left(\frac{D_p}{L_p N_D} \right) (e^{V/V_T} - 1)$$

$$I_n = A q n_i^2 \left(\frac{D_n}{L_n N_A} \right) (e^{V/V_T} - 1)$$

$$\therefore \frac{I_P}{I_n} = \frac{D_p L_n N_A}{D_n L_p N_D} = \frac{10 \times 10 \times 10^{18}}{20 \times 5 \times 10^{18}} = \underline{100}$$

$$I = I_P + I_n = 100 I_n + I_n = 1 \text{ mA}$$

$$I_n = 1/101 = \underline{9.9 \mu A}$$

$$I_P = 100(9.9) = \underline{990 \mu A}$$

3.121

$$I_P = A q n_i^2 \frac{D_p}{L_p N_D} (e^{V/V_T} - 1)$$

$$I_n = A q n_i^2 \frac{D_n}{L_n N_A} (e^{V/V_T} - 1)$$

$$\text{For } p^+ - n \quad N_A \gg N_D$$

$$\therefore I \cong I_P = A q n_i^2 \frac{D_p}{L_p N_D} (e^{V/V_T} - 1)$$

$$I_0 \cong A q n_i^2 \frac{D_p}{L_p N_D} = A q n_i^2 \left(\frac{D_p}{\sqrt{D_p \tau_p} N_D} \right)$$

$$= 10^4 (10^{-8}) 1.6 \times 10^{-19} \frac{(1.5 \times 10^{-10})^2}{\sqrt{10 \times 0.1 \times 10^{-6}} \times 5 \times 10^{16}}$$

$$= \underline{0.72 \times 10^{-15} \text{ A}}$$

CONT.

$$I = I_s (e^{V/V_T} - 1) = 0.2 \times 10^{-3}$$

$$0.72 \times 10^{-5} (e^{V/0.025} - 1) = 0.2 \times 10^{-3}$$

$$V = \underline{0.684 V}$$

Excess minority charge

$$= Q_p + Q_n$$

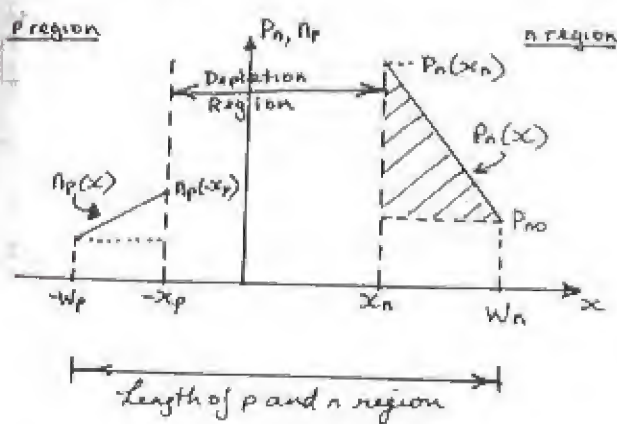
$$= \tau_p I_p + \tau_n I_n \approx \tau_p I_p$$

$$= (0.1 \times 10^{-6}) (0.2 \times 10^{-3}) = \underline{2 \times 10^{-11} C}$$

$$C_d = \frac{\tau_p I}{V_T} \approx \frac{\tau_p I}{V_T}$$

$$= 0.1 \times 10^{-6} \times \frac{0.2 \times 10^{-3}}{0.025} = \underline{800 pF}$$

3.122



(a) First consider I_p :

$$P_n(x_n) = P_{n0} e^{V/V_T}$$

$$I_p = A J_p, \text{ and}$$

$$P_{n0} = \frac{n_i^2}{N_D}$$

$$\text{Thus, } I_p = A q n_i^2 \frac{D_p}{(W_n - x_n) N_D} (e^{V/V_T} - 1)$$

$$\& I_n = A q n_i^2 \frac{D_n}{(W_p - x_p) N_A} (e^{V/V_T} - 1)$$

$$\text{Thus: } I = I_p + I_n$$

$$= A q n_i^2 \left[\frac{D_p}{(W_n - x_n) N_D} + \frac{D_n}{(W_p - x_p) N_A} \right] \times (e^{V/V_T} - 1) \text{ Q.E.D.}$$

The excess charge, Q_p , can be found by multiplying the area of the shaded triangle of the $P_n(x)$ distribution graph by Aq .

$$Q_p = A q \times \frac{1}{2} [P_n(x_n) - P_{n0}] [W_n - x_n]$$

$$= \frac{1}{2} A q P_{n0} (e^{V/V_T} - 1) (W_n - x_n)$$

$$= \frac{1}{2} A q \frac{n_i^2}{N_D} (W_n - x_n) (e^{V/V_T} - 1)$$

$$= \frac{1}{2} \frac{(W_n - x_n)^2}{D_p} I_p$$

$$\approx \frac{1}{2} \frac{W_n^2}{D_p} I_p \text{ for } W_n \gg x_n$$

Q.E.D. //

$$(c) C_d = \frac{dQ}{dV} = \tau_p \frac{dI}{dV} \text{ But } I = I_s (e^{V/V_T} - 1)$$

$$\therefore C_d \approx \frac{\tau_p I}{V_T} \quad \frac{dI}{dV} = \frac{I_s e^{V/V_T}}{V_T} \approx I/V_T$$

$$(d) C_d = \frac{1}{2} \frac{W_n^2}{D_p} \times \frac{10^{-3}}{0.025} = 8 \times 10^{-12}$$

$$W_n = \underline{63.2 \mu m}$$

Chapter 4 - Problems

4.1

The capacitance per unit area is: $C_{ox} = \frac{\epsilon_{ox}}{t_{ox}}$

$$\epsilon_{ox} = 3.45 \times 10^{-11} \text{ F/m}$$

$$t_{ox} = 5 \text{ nm} \Rightarrow C_{ox} = \frac{3.45 \times 10^{-11}}{5 \times 10^{-9}} = 6.9 \text{ fF}/\mu\text{m}^2$$

$$t_{ox} = 10 \text{ nm} \Rightarrow C_{ox} = 0.86 \text{ fF}/\mu\text{m}^2$$

For 1pF capacitance, we require an area A:

$$A = \frac{10^{-12}}{6.9 \times 10^{-15}} = 145 \mu\text{m}^2 \text{ for } t_{ox} = 5 \text{ nm}$$

$$A = \frac{10^{-12}}{0.86 \times 10^{-15}} = 1163 \mu\text{m}^2 \text{ for } t_{ox} = 20 \text{ nm}$$

For a square plate capacitor of 10pF:

$$A = 10 \times 145 = 1450 \mu\text{m}^2 \text{ or } 38 \times 38 \mu\text{m}^2 \text{ square for } t_{ox} = 5 \text{ nm}$$

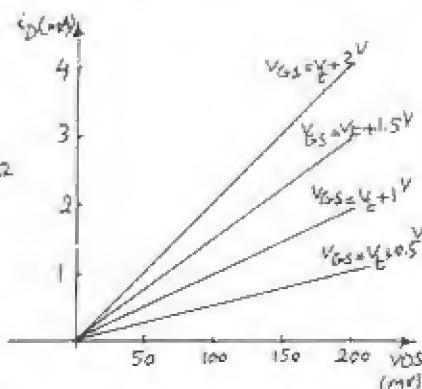
$$A = 10 \times 1163 = 11630 \mu\text{m}^2 \text{ or } 108 \times 108 \mu\text{m}^2 \text{ square for } t_{ox} = 20 \text{ nm}$$

4.2

Drain current is directly proportional to the width of the channel. Therefore if width is 10 times greater, then i_D would be 10 times greater as well.

$K = \text{Constant of proportionality} =$

$$\frac{1}{0.5 \times 0.2} = 10 \text{ mA}/V^2$$



$$r_{DS} = \frac{i_D}{V_{DS}} = \frac{1}{0.2} = 5 \text{ k}\Omega \text{ for } V_{GS} = 0.5 \text{ V}$$

$$r_{DS} = 10 \text{ k}\Omega \text{ for } V_{GS} = 1 \text{ V}$$

$$r_{DS} = 15 \text{ k}\Omega \text{ for } V_{GS} = 1.5 \text{ V}$$

$$r_{DS} = 20 \text{ k}\Omega \text{ for } V_{GS} = 2 \text{ V}$$

$$5 \text{ k}\Omega \leq r_{DS} \leq 20 \text{ k}\Omega \text{ for } 0.5 \text{ V} \leq V_{GS} \leq 2 \text{ V}$$

4.3

$$\text{eq. 4.6a: } i_D = \frac{1}{2} K'_n \frac{W}{L} (V_{GS} - V_T)^2 \quad K'_n = \mu_n C_{ox}$$

for equal drain currents:

$$\mu_n C_{ox} \frac{W_n}{L} = \mu_p C_{ox} \frac{W_p}{L} \Rightarrow \frac{W_p}{W_n} = \frac{\mu_n}{\mu_p} = \frac{1}{0.4} = 2.5$$

4.4

$$\text{for small } V_{DS}: i_D \approx K'_n \frac{W}{L} (V_{GS} - V_T) V_{DS}$$

$$r_{DS} = \frac{V_{DS}}{i_D} = \frac{1}{K'_n \frac{W}{L} (V_{GS} - V_T)} = \frac{1}{50 \times 10^{-6} \times 20 \times (5 - 0.8)}$$

$$r_{DS} = 238 \Omega \quad V_{DS} = r_{DS} \times i_D = 238 \text{ mV}$$

for the same performance of a p-channel

$$\text{device: } \frac{W_p}{W_n} = \frac{\mu_n}{\mu_p} = 2.5 \Rightarrow \frac{W_p}{L} = \frac{W_n \times 2.5}{L} = 20 \times 2.5$$

$$\Rightarrow \frac{W_p}{L} = 50$$

4.5

$$\text{Eq 4.5a: } i_D = K'_n \frac{W}{L} \left[(V_{GS} - V_T) V_{DS} - \frac{1}{2} V_{DS}^2 \right] \text{ triode region}$$

for small V_{DS} :

$$i_D \approx K'_n \frac{W}{L} (V_{GS} - V_T) V_{DS}$$

$$r_{DS} = \frac{V_{DS}}{i_D} = \frac{1}{K'_n \frac{W}{L} (V_{GS} - V_T)}$$

for $r_{DS} = 1 \text{ k}\Omega$:

$$K'_n = 100 \text{ mA}/V^2: 1000 = \frac{1}{100 \times 10^{-6} \frac{W}{L} \times (5 - 0.8)} \Rightarrow W = 2.4 \mu\text{m}$$

4.6

$$\text{a) } C_{ox} = \frac{\epsilon_{ox}}{t_{ox}} = \frac{3.45 \times 10^{-11}}{15 \times 10^{-9}} = 2.3 \text{ fF}/\mu\text{m}^2$$

$$K'_n = \mu_n C_{ox} = 550 \times 10^{-4} \times 2.3 \times 10^{-3} = 126.5 \text{ mA}/V^2$$

$$\text{b) } i_D = \frac{1}{2} K'_n \frac{W}{L} (V_{GS} - V_T)^2 \Rightarrow 100 = \frac{1}{2} \times 126.5 \times \frac{16}{0.8} (V_{GS} - 0.7)^2$$

$$V_{GS} - 0.7 = 0.28 \Rightarrow V_{GS} = 0.98 \text{ V}$$

$$V_{DSmin} = V_{GS} - V_T = 0.28 \text{ V}$$

$$\text{c) for small } V_{DS} \text{ (triode region)} i_D \approx K'_n \frac{W}{L} V_{OV} V_{DS}$$

Cont.

$$r_{DS} = \frac{V_{DS}}{i_D} = \frac{1}{K_n \frac{W}{L} V_{OV}} = \frac{1}{126.5 \times 10^6 \times \frac{16}{0.8} V_{OV}} = 1000$$

$$\rightarrow V_{OV} = 0.4V$$

$$V_{GS} = V_{OV} + V_t = 0.4 + 0.7 = 1.1V$$

4.7

$$K_n' = \mu_n C_{ox} = \mu_n \frac{\epsilon_{ox}}{t_{ox}} = 650 \times 10^4 \times \frac{3.45 \times 10^{-11}}{20 \times 10^{-9}} = 112.1 \mu A/V^2$$

a) triode region: $V_{DS} < V_{GS} - V_t$

$$i_D = K_n' \frac{W}{L} \left[(V_{GS} - V_t) V_{DS} - \frac{1}{2} V_{DS}^2 \right]$$

$$i_D = 112.1 \times 10^6 \times 10 \left[(5 - 0.8) \times 1 - \frac{1}{2} \times 1^2 \right] = 4.15 mA$$

b) edge of saturation region: $V_{DS} = V_{GS} - V_t$

$$i_D = \frac{1}{2} K_n' \frac{W}{L} (V_{GS} - V_t)^2 = \frac{1}{2} \times 112.1 \times 10^6 \times 10 \times (1.2)^2 = 0.8 mA$$

c) triode region: $V_{DS} < V_{GS} - V_t$

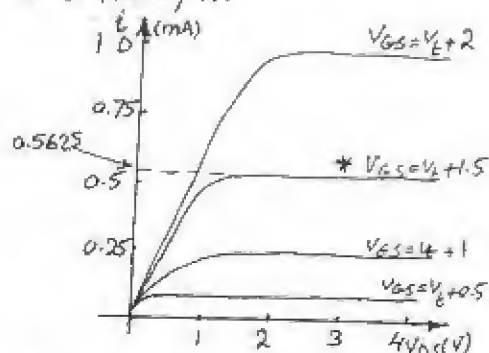
$$i_D = 112.1 \times 10^6 \times 10 \left[(5 - 0.8) \times 0.2 - \frac{1}{2} \times 0.2^2 \right] = 0.92 mA$$

d) Saturation region: $V_{DS} > V_{GS} - V_t$

$$i_D = \frac{1}{2} \times 112.1 \times 10^6 \times 10 \times (5 - 0.8)^2 = 9.9 mA$$

4.8

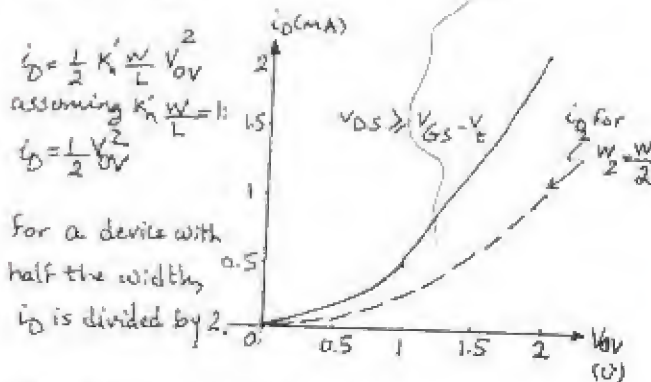
Refer to Fig. 4.11b, $i_D \propto \frac{W}{L}$ so if W is halved, then i_D would also be halved. The vertical axis, i_D , has to be divided by 2:



For $V_{OV} = 1.5V$, by looking at the corresponding curve, $V_{GS} = V_t + 1.5$, we observe that:
 $i_D = 0.5625 mA$

4.9

4.10



For a device with half the width, i_D is divided by 2.

This graph is not dependent on V_t , while Fig. 4.12 is dependent on V_t .

4.11

$$\text{Eq. 4.13: } r_{DS} = \left[K_n' \frac{W}{L} (V_{GS} - V_t) \right]^{-1} \text{ therefore:}$$

$$\frac{r_{DS1}}{r_{DS2}} = \frac{V_{GS2} - V_t}{V_{GS1} - V_t} \Rightarrow \frac{1000}{200} = \frac{V_{GS2} - 1}{1.5 - 1} \Rightarrow V_{GS2} = 3.5V$$

Now for a device with twice the width:

Cont.

$$\frac{r_{DS1}}{r_{DS2}} = \frac{W_2(V_{GS2} - V_t)}{W_1(V_{GS2} - V_t)}$$

$$\text{for } V_{GS} = 1.5V \quad \frac{r_{DS1}}{r_{DS2}} = 2 \Rightarrow r_{DS2} = \frac{1000}{2} = 500\Omega$$

$$\text{for } V_{GS} = 3.5V \quad \frac{r_{DS2}}{r_{DS1}} = \frac{200}{2} = 100\Omega$$

4.12

$$i_D = \frac{1}{2} K'_n \frac{W}{L} (V_{GS} - V_t)^2 \Rightarrow 0.2 \times 10^{-3} = \frac{1}{2} \times 0.1 \times 10^{-3} (V_{GS} - 1)^2$$

$$V_{GS} - 1 = 2 \Rightarrow V_{GS} = 3V$$

$$V_{DSmin} = V_{GS} - V_t = 3 - 1 = 2V$$

$$\text{for } i_D = 0.8mA: 0.8 = \frac{1}{2} \times 0.1 (V_{GS} - 1)^2$$

$$V_{GS} - 1 = 4 \Rightarrow V_{GS} = 5V$$

$$V_{DSmin} = V_{GS} - V_t = 5 - 1 = 4V$$

4.13

$V_{GS} = V_{DS}$ indicates operation in saturation mode: $i_D = \frac{1}{2} K'_n \frac{W}{L} (V_{GS} - V_t)^2$

$$\left. \begin{aligned} 4 &= \frac{1}{2} K'_n \frac{W}{L} (5 - V_t)^2 \\ 1 &= \frac{1}{2} K'_n \frac{W}{L} (3 - V_t)^2 \end{aligned} \right\} \Rightarrow 4 = \frac{(5 - V_t)^2}{(3 - V_t)^2} \Rightarrow$$

$$(5 - V_t) = 2(3 - V_t) \Rightarrow V_t = 1V, \quad K'_n \frac{W}{L} = 0.5 mA/V^2$$

4.14

$$i_D = \frac{1}{2} K'_n \frac{W}{L} (V_{GS} - V_t)^2 \Rightarrow 0.8 = \frac{1}{2} \times 50 \times 10^{-6} \frac{W}{L} (5 - 1)^2$$

$$\frac{W}{L} = 2 \Rightarrow W = 2 \times 2 = 4\mu m$$

4.15

In triode region: $i_D = K'_n \frac{W}{L} [(V_{GS} - V_t)V_{DS} - \frac{V_{DS}^2}{2}]$

$$\frac{i_{D1}}{i_{D2}} = \frac{60\mu A}{160\mu A} = \frac{(2 - V_t)(0.1 - 0.01/2)}{(4 - V_t)(0.1 - 0.01/2)} \Rightarrow V_t = 0.75V$$

$$\text{if } K'_n = 50 \mu A/V^2: 60 = 50 \frac{W}{L} [(2 - 0.75)0.1 - \frac{0.01}{2}]$$

$$\frac{W}{L} = 10$$

$$\text{If } V_{GS} = 3V, V_{DS} = 0.15V \text{ then } i_D = 50 \times 10 \times [2.25 \times 0.15 - \frac{0.15^2}{2}]$$

$$i_D = 163.125 \mu A$$

If $V_{GS} = 3V$, the channel reaches pinch-off at

$$V_{DS} = V_{GS} - V_t = 3 - 0.75 = 2.25V \text{ for which:}$$

$$i_D = \frac{1}{2} \times K'_n \frac{W}{L} (V_{GS} - V_t)^2 = \frac{1}{2} \times 50 \times 10 \times 2.25^2 = 1.3mA$$

$$i_D = 1.3mA$$

4.16

For the channel to remain continuous:

$$V_{DS} \leq V_{GS} - V_t \Rightarrow V_{DSmax} = 1.5 - 0.8 = 0.7V$$

4.17

$$\text{Eq. 4.15: } r_{DS} = \left[K'_n \frac{W}{L} V_{OV} \right]^{-1} = \frac{1}{50 \times \frac{100}{8} (V_{GS} - 1)} \text{ M}\Omega$$

$$r_{DS} = \frac{1}{V_{GS} - 1} \text{ K}\Omega$$

$$V_{GS} = 1.1V \Rightarrow r_{DS} = 10K\Omega$$

$$V_{GS} = 11V \Rightarrow r_{DS} = 100\Omega$$

$$\Rightarrow 100\Omega \leq r_{DS} \leq 10K\Omega$$

a) $r_{DS} \propto \frac{1}{W}$ so if W is halved, r_{DS} is doubled:
 $200\Omega \leq r_{DS} \leq 20K\Omega$

b) $r_{DS} \propto L$ so if L is halved, r_{DS} is also halved: $50\Omega \leq r_{DS} \leq 5K\Omega$

c) $r_{DS} \propto \frac{L}{W}$ so if both W and L are halved, $\frac{W}{L}$ stays unchanged and so does r_{DS} .
 $100\Omega \leq r_{DS} \leq 10K\Omega$

4.18

According to eq. 4.17: $V_{GD} \leq V_t$ for saturation region. Since V_{GD} is zero in Fig. P4.18, then the device is always in saturation region:

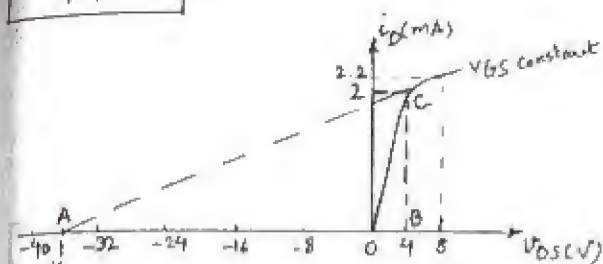
$$i_D = i = \frac{1}{2} K'_n \frac{W}{L} (V_{GS} - V_t)^2$$

if we replace V_{GS} by V and $K' = \frac{1}{2} K'_n$

$$i = K' \frac{W}{L} (V - V_t)^2$$

$$r = \left(\frac{\partial i}{\partial V} \right)^{-1} = \frac{1}{2K' \frac{W}{L} (V - V_t)} = \frac{1}{K'_n \frac{W}{L} V_{OV}} \text{ where } V = |V_t| + V_{OV}$$

4.19



$$r_o = \frac{\Delta V_{DS}}{\Delta i_D} \bigg|_{V_{GS} \text{ const}} = \frac{8-4}{2.2-2} = 20 \text{ k}\Omega$$

To calculate V_A , consider the ABC triangle.

$$V_A + 4 = 2 \text{ mA} \times r_o = 2 \times 20 = 40 \text{ V} \Rightarrow V_A = 36 \text{ V}$$

$$\lambda = \frac{1}{V_A} = 0.028 \text{ V}^{-1}$$

4.20

Eq. 4.26: $r_o = \frac{V_A}{i_D} = \frac{50}{0.1 \text{ mA}} = 500 \text{ k}\Omega$
 $r_o = \frac{\Delta V_{DS}}{\Delta i_D} \Rightarrow \Delta i_D = \frac{\Delta V_{DS}}{r_o} = \frac{1}{r_o}$

$$i_D = 0.1 \text{ mA} \quad \Delta i_D = 2 \text{ }\mu\text{A} \quad \frac{\Delta i_D}{i_D} = 2\%$$

$$i_D = 1 \text{ mA} \quad \Delta i_D = 20 \text{ }\mu\text{A} \quad \frac{\Delta i_D}{i_D} = 2\%$$

4.21

$V_A = V_A' L$ where V_A' is completely process dependent. Also, $r_o = \frac{V_A}{i_D}$. Therefore to achieve desired r_o (which is 4 times larger), we should increase L . $L = 4 \times 2 = 8 \text{ }\mu\text{m}$

In order to keep I_D unchanged, $\frac{W}{L}$ ratio has to stay unchanged. Therefore:

$$W = 4 \times 10 = 40 \text{ }\mu\text{m} \quad (\text{So } \frac{W}{L} \text{ is kept at } 5)$$

$$V_A = r_o i_D = 0.5 \text{ M}\Omega \times 100 \text{ }\mu\text{A} = 50 \text{ V} \quad (\text{For standard})$$

$$V_A = 4 \times 0.5 \text{ M}\Omega \times 100 = 200 \text{ V} \quad (\text{For new device})$$

4.22

$$\lambda = 0.02 \text{ V}^{-1} \Rightarrow V_A = 50 \text{ V} \quad \text{for } L = 1 \text{ }\mu\text{m}$$

$$V_A = V_A' L \Rightarrow V_A' = 50 \text{ V}$$

$$\text{For } L = 3 \text{ }\mu\text{m}: V_A = 50 \times 3 = 150 \text{ V}$$

$$r_o = \frac{V_A}{i_D} = \frac{150}{0.08} = 1875 \text{ k}\Omega$$

$$r_o = \frac{\Delta V_{DS}}{\Delta i_D} \Rightarrow \Delta i_D = \frac{\Delta V_{DS}}{r_o} = \frac{5-1}{1875} = 2.13 \text{ }\mu\text{A}$$

For V_{DS} raised from 1V to 5V, i_D increases from 80 μA to 82.13 μA .

$$\frac{\Delta i_D}{i_D} = 2.7\% \text{ change in } i_D$$

In order to reduce $\frac{\Delta i_D}{i_D}$ by a factor of 2, Δi_D has to be halved, or equivalently r_o has to be doubled. In order to double r_o , V_A has to be doubled and this can be done by doubling the length. $L = 2 \times 3 = 6 \text{ }\mu\text{m}$

4.23

$$V_A = V_A' L = 20 \times 1.6 = 32 \text{ V}, \quad \lambda = \frac{1}{V_A} = 0.031 \text{ V}^{-1}$$

$$V_{DS} = 2 \text{ V} > (V_{GS} - V_t) = 0.5 \text{ V} \Rightarrow \text{device in saturation region}$$

$$i_D = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} V_{DS}^2 = \frac{1}{2} \times 130 \times \frac{16}{1.6} \times 0.5^2 = 162.5 \text{ }\mu\text{A}$$

$$r_o = \frac{V_A}{i_D} = \frac{32}{162.5 \text{ }\mu\text{A}} = 197 \text{ k}\Omega$$

$$r_o = \frac{\Delta V_{DS}}{\Delta i_D} \Rightarrow \Delta i_D = \frac{\Delta V_{DS}}{r_o} = \frac{1}{197 \text{ k}\Omega} \Rightarrow \Delta i_D = 5.1 \text{ nA}$$

4.24

MOS	1	2	3	4
$\lambda (\text{V}^{-1})$	0.02	0.01	0.1	0.005
$V_A (\text{V})$	50	100	10	200
$I_D (\text{mA})$	5	3.33	0.1	0.2
$r_o (\text{k}\Omega)$	10	30	100	1000
$r_o = \frac{V_A}{I_D}, \lambda = \frac{1}{V_A}$				


4.25

$V_A = \frac{1}{\lambda} = 100 \text{ V}$ $V_A = V_A' L$ if L is doubled, so is V_A .
 $V_A = 2 \times 100 = 200 \text{ V}, \lambda = \frac{1}{200} = 0.005 \text{ V}^{-1}$
 a) if V_{GS} is fixed, then i_D is halved, as a result of doubling L . $I_D \propto \frac{1}{L} \Rightarrow I_D = \frac{1}{2} = 0.5 \text{ mA}$
 Cont.

$$r_D = \frac{V_A}{I_D} = \frac{200}{0.5} = 400 \text{ k}\Omega$$

b) if I_D is fixed: $r_D = \frac{V_A}{I_D} = \frac{200}{1} = 200 \text{ k}\Omega$

4.26

$V_{GS} = -5 \text{ V}$
 To operate in saturation: 
 $V_{DS} \leq V_{GS} - V_t$ or $V_{DS} \leq -5 - (-1.5)$ or $V_{DS} \leq -3.5$

a) $V_D = 4 \text{ V} \Rightarrow V_{DS} = -1 \text{ V} > -3.5 \text{ V} \Rightarrow$ triode region

$$i_D = K'_p \frac{W}{L} \left[(V_{GS} - V_t) V_{DS} - \frac{1}{2} V_{DS}^2 \right] \quad \text{eq. 4.29}$$

$$i_D = 80 \left[(-5 - (-1.5))(-1) - \frac{1}{2}(-1)^2 \right] = 0.24 \text{ mA}$$

b) $V_D = 1.5 \text{ V} \Rightarrow V_{DS} = -3.5 \text{ V} = V_{GS} - V_t \Rightarrow$ edge of saturation

$$i_D = \frac{1}{2} K'_p \frac{W}{L} (V_{GS} - V_t)^2 (1 + \lambda V_{DS}) \quad \text{eq. 4.32}$$

$$i_D = \frac{80}{2} (3.5)^2 (1 + 0.02 \times 3.5) = 0.52 \text{ mA}$$

c) $V_D = 0 \Rightarrow V_{DS} = -5 \text{ V} < -3.5 \Rightarrow$ saturation

$$i_D = \frac{1}{2} \times 80 \times (3.5)^2 (1 + 0.02 \times 5) = 0.54 \text{ mA}$$

d) $V_D = -5 \text{ V} \Rightarrow V_{DS} = -10 \text{ V} < -3.5 \Rightarrow$ saturation

$$i_D = \frac{1}{2} \times 80 \times (3.5)^2 (1 + 0.02 \times 10) = 0.59 \text{ mA}$$

4.27

$V_{GS} = -3 \text{ V} \quad V_{SG} = 3 \text{ V} \quad V_t = -1 \text{ V}$
 $V_{DS} = -4 \text{ V} \quad V_{SD} = 4 \text{ V} \quad V_A = -50 \text{ V} \quad \lambda = 0.02 \text{ V}^{-1}$
 $i_D = \frac{1}{2} K'_p \frac{W}{L} (V_{GS} - V_t)^2 (1 + \lambda V_{DS})$
 $3 = \frac{1}{2} K'_p \frac{W}{L} (-3 + 1)^2 (1 + 0.02 \times 4) = 2.16 K'_p \frac{W}{L}$
 $K'_p \frac{W}{L} = 1.39 \text{ mA/V}^2$

4.28

Eq. 4.34: $Y = \sqrt{29 N_A \epsilon_s} \Rightarrow N_A = \frac{Y^2}{29 \epsilon_s}$
 $t_{ox} = 20 \text{ nm} \quad C_{ox} = \frac{\epsilon_{ox}}{t_{ox}} = \frac{3.45 \times 10^{-11}}{20 \times 10^{-9}} = 1.73 \text{ fF}/\mu\text{m}^2$

$$N_A = \frac{0.5^2 \times 1.73 \times 10^{-6}}{2 \times 1.6 \times 10^{-19} \times 11.7 \times 8.854 \times 10^{-14} \times 10^2} = 2.3 \times 10^{22} / \text{m}^3$$

$$N_A = 2.3 \times 10^{16} / \text{cm}^3$$

if $t_{ox} = 100 \text{ nm} \quad \frac{\gamma_1}{\gamma_2} = \frac{C_{ox2}}{C_{ox1}} = \frac{t_{ox1}}{t_{ox2}} \Rightarrow \frac{0.5}{\gamma_2} = \frac{20}{100}$
 $\Rightarrow \gamma_2 = 2.5 \text{ V}^{1/2}$

if γ is kept at $0.5 \text{ V}^{1/2}$, then when t_{ox} is changed:
 $\frac{\sqrt{N_{A1}}}{C_{ox1}} = \frac{\sqrt{N_{A2}}}{C_{ox2}} \Rightarrow \frac{\sqrt{N_{A1}}}{\sqrt{N_{A2}}} = \frac{C_{ox1}}{C_{ox2}} = \frac{t_{ox2}}{t_{ox1}} = \frac{100}{20} = 5$

$$\sqrt{N_{A2}} = \frac{\sqrt{N_{A1}}}{5} \Rightarrow N_{A2} = \frac{N_{A1}}{25} = 9.2 \times 10^{14} / \text{cm}^3$$

4.29

Eq. 4.33 $V_t = V_{t0} + \gamma \left[\sqrt{2\phi_F + V_{SB}} - \sqrt{2\phi_F} \right]$

$V_{SB} = 0 \text{ V} \Rightarrow V_t = V_{t0} = 1 \text{ V}$

$V_{SB} = 4 \text{ V} \Rightarrow V_t = 1 + 0.5 \left[\sqrt{0.6 + 4} - \sqrt{0.6} \right] = 1.69 \text{ V}$

$1 \text{ V} \leq V_t \leq 1.69 \text{ V}$

If t_{ox} is increased by a factor of 4:

From Eq. 4.34 $\gamma \propto \frac{1}{C_{ox}}$ or $\gamma \propto t_{ox}$ or $\frac{\gamma_1}{\gamma_2} = \frac{t_{ox1}}{t_{ox2}}$

$\Rightarrow \gamma_2 = 4 \times 0.5 = 2 \text{ V}^{1/2}$

$V_t = 1 + 2 \left(\sqrt{0.6 + 4} - \sqrt{0.6} \right) = 3.74 \text{ V}$ for $V_{SB} = 2 \text{ V}$

$V_t = 1 \text{ V}$ for $V_{SB} = 0$

Therefore for $\gamma = 2$: $1 \leq V_t \leq 3.74 \text{ V}$

4.30

$|V_{SB}| = 3 \text{ V}$ Eq. 4.33 $V_t = V_{t0} + \gamma \left[\sqrt{2\phi_F + V_{SB}} - \sqrt{2\phi_F} \right]$
 $V_t = -1 - 0.5 \left[\sqrt{0.6 + 3} - \sqrt{0.6} \right] = -1.56 \text{ V}$

4.31

a) $i_D = \frac{1}{2} K'_n \frac{W}{L} (V_{GS} - V_t)^2$
 $\frac{\partial i_D}{\partial T} = \frac{1}{2} \frac{W}{L} \frac{\partial K'_n}{\partial T} (V_{GS} - V_t)^2 - K'_n \frac{W}{L} (V_{GS} - V_t) \frac{\partial V_t}{\partial T}$
 $\frac{\partial i_D / i_D}{\partial T} = \frac{\partial K'_n / K'_n}{\partial T} - \frac{2 \partial V_t}{\partial T} \frac{1}{V_{GS} - V_t}$

Cont.

b) $\frac{\partial V_E}{\partial T} = -2 \text{ mV}/^\circ\text{C}$ For $\frac{\partial i_D/i_D}{\partial T} = -0.2\% = -0.002/^\circ\text{C}$

$$-0.002 = \frac{\partial k_n/k_n}{\partial T} - 2 \times (-2\%) \frac{1}{5-1} \Rightarrow \frac{\partial k_n/k_n}{\partial T} = -0.003/^\circ\text{C} = -0.3\%/^\circ\text{C}$$

4.32

Case	Transistor	V_S	V_G	V_D	I_D	type	mode	$\mu_n C_{ox} \frac{W}{L}$	V_E
a	1	0	2	5	100	N	Sat.	200	1
	1	0	3	5	400	N	Sat.	200	1
b	2	5	3	-15	50	P	Sat.	400	-1.5
	2	5	2	-0.5	450	P	Sat.	400	-1.5
c	3	5	3	4	200	P	Sat.	400	-1
	3	5	2	0	800	P	Sat.	400	-1
d	4	-2	0	0	72	N	Sat.	100	0.8
	4	-4	0	-3	270	N	Triode	100	0.8

Case a) transistor 1: $V_{GS} = 2\text{V}$ $V_{DS} = 5\text{V}$ $I_D = 100\mu\text{A}$
This must be an NMOS operating in saturation.

$$I_D = 100 = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (2 - V_E)^2$$

$$\text{When } V_{GS} = 3\text{V: } 400 = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (3 - V_E)^2 \Rightarrow 4 = \frac{(3 - V_E)^2}{(2 - V_E)^2}$$

$$\Rightarrow 2(2 - V_E) = 3 - V_E \Rightarrow V_E = 1\text{V}, \mu_n C_{ox} \frac{W}{L} = \frac{200\mu\text{A}}{\text{V}^2}$$

Case b) transistor 2: $V_{GS} = 3 - 5 = -2\text{V}$ $V_{DS} = -9.5\text{V}$
Therefore $V_{DS} < V_{GS} - V_E$ regardless of value of V_E , and the device operates in saturation (PMOS)

$$I_D = 50 = \frac{1}{2} \mu_p C_{ox} \frac{W}{L} (-2 - V_E)^2$$

$$450 = \frac{1}{2} \mu_p C_{ox} \frac{W}{L} (-3 - V_E)^2 \Rightarrow 9 = \frac{(3 + V_E)^2}{(2 + V_E)^2}$$

$$\Rightarrow 3(2 + V_E) = 3 + V_E \Rightarrow V_E = -1.5\text{V}, \mu_p C_{ox} \frac{W}{L} = \frac{400\mu\text{A}}{\text{V}^2}$$

Case c) transistor 3: $V_{GS} = -2\text{V}$ $V_{DS} = -1\text{V} \Rightarrow$ PMOS
This device can be either in saturation or triode region. First, we assume saturation region:

$$I_D = 200 = \frac{1}{2} \mu_p C_{ox} \frac{W}{L} (-2 - V_E)^2$$

$$800 = \frac{1}{2} \mu_p C_{ox} \frac{W}{L} (-3 - V_E)^2 \Rightarrow 4 = \frac{(3 + V_E)^2}{(2 + V_E)^2}$$

$$\Rightarrow 2(2 + V_E) = 3 + V_E \Rightarrow V_E = -1\text{V}, \mu_p C_{ox} \frac{W}{L} = \frac{400\mu\text{A}}{\text{V}^2}$$

So our assumption was right:

$$(V_{DS} = -1\text{V}) \ll (V_{GS} - V_E) = -2 - (-1) = -1\text{V}$$

edge of saturation

Case d) transistor 4: $V_{GS} = 2\text{V}$ $V_{DS} = 2\text{V} \Rightarrow$ NMOS
So $V_{DS} > V_{GS} - V_E \Rightarrow$ saturation region

$$\textcircled{1} I_D = 72 = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (2 - V_E)^2$$

But for $V_{GS} = 4\text{V}$, $V_{DS} = 1\text{V}$ and considering that $V_E < 2\text{V}$, then the device is in triode region:

$$270 = \mu_n C_{ox} \frac{W}{L} \left[(4 - V_E) \times 1 - \frac{1}{2} \times 1 \right]$$

$$\textcircled{2} 270 = \mu_n C_{ox} \frac{W}{L} (3.5 - V_E)$$

$$\textcircled{1}, \textcircled{2} \Rightarrow V_E = 0.8\text{V}, \mu_n C_{ox} \frac{W}{L} = 100\mu\text{A}/\text{V}^2$$

4.33

$$\text{a) } I_D = \frac{1}{2} k_n' \frac{W}{L} (V_{GS} - V_E)^2 \Rightarrow 2 = \frac{1}{2} k_n' \frac{W}{L} (3 - 1)^2$$

$$\Rightarrow k_n' \frac{W}{L} = 1 \text{ mA}/\text{V}^2$$

$$V_i = V_{DS} = 3\text{V}$$

$$\text{b) } V_2 = V_S - V_D - V_{DS} = 1 - 3 = -2\text{V}$$

$$\text{c) } V_3 = V_S - V_D - V_{DS} = 0 - (-3) = 3\text{V}$$

$$\text{d) } V_4 = V_D - V_S + V_{DS} = 5 + (-3) = 2\text{V}$$

In order to calculate R_{Dmax} that can be inserted in series with the drain, V_{DS} has to be equal to $V_{GS} - V_E$, so that the device is operating on the edge of saturation:
 $|V_{DS}| = 3 - 1 = 2\text{V}$. Note that since i_D is the same, V_{GS} stays the same.

$$\text{a) } R_{Dmax} = \frac{3 - 1}{2 \text{ mA}} = 0.5 \text{ k}\Omega$$

$$\text{b) } V_2 = -2\text{V} \Rightarrow V_D = -2 + 2 = 0 \Rightarrow R_{Dmax} = \frac{1}{0.5 \text{ mA}} = 0.5 \text{ k}\Omega$$

Note that V_2 is fixed through $V_{GS} = 3\text{V}$.

$$\text{c) } V_{GS} = -3\text{V} \Rightarrow V_S = V_3 = 3\text{V}$$

Now for V_{DS} to be -2V , V_D has to be 1V .

$$R_{Dmax} = \frac{1\text{V}}{2 \text{ mA}} = 0.5 \text{ k}\Omega$$

$$\text{d) } V_{GS} = -3\text{V} \Rightarrow V_E = V_4 = 2\text{V}$$

Adding the resistor between V_4 and drain means that V_D has to be $5 - 2 = 3\text{V}$ and this leaves 1V voltage drop on the resistor: $R_{Dmax} = \frac{1}{2} = 0.5 \text{ k}\Omega$

In order to calculate the largest resistor added to the gates, note that since the gate doesn't draw any current, the value of the resistor is immaterial.

Cont.

Now we calculate R_{Smax} , assuming that the voltage drop across the current source is at least $2V$:

a) $V_1 = 8V$ then $V_{GS} = 3V \Rightarrow V_S = 8 - 3 = 5V$

$$R_{Smax} = \frac{5}{2} = 2.5 k\Omega$$

b) $V_2 = -9 + 2 = -7V$, $V_S = 1 - |V_{GS}| = -2V$

$$R_{Smax} = \frac{-2 - (-7)}{2} = 2.5 k\Omega$$

c) $V_3 = 10 - 2 = 8V$, $V_S = 0 + |V_{GS}| = 3V$

$$R_{Smax} = \frac{8-3}{2} = 2.5 k\Omega$$

d) $V_4 = -5 + 2 = -3V$, $V_S = -3 + |V_{GS}| = 0V$

$$R_{Smax} = \frac{5}{2} = 2.5 k\Omega$$

4.34

$$I_D = \frac{V_{DD} - V_D}{R_D} \Rightarrow \frac{5-0}{R_D} = 1 mA \Rightarrow R_D = 5 k\Omega$$

$$V_D = V_G \Rightarrow \text{saturation}$$

therefore: $I_D = \frac{1}{2} K'_n \frac{W}{L} (V_{GS} - V_t)^2$

$$1 = \frac{1}{2} \times 60 \times 10^{-3} \times \frac{100}{3} (V_{GS} - 1)^2$$

$$\Rightarrow V_{GS} = 2V \Rightarrow V_S = -2V$$

$$R_S = \frac{-2 - (-5)}{1} = 3 k\Omega$$

4.35

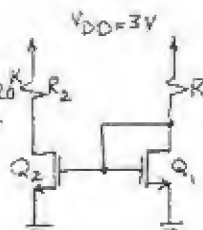
a) $I_D = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_t)^2$

$$I_{D1} = 0.2 = \frac{1}{2} \times 200 \times 10^{-6} \times \frac{8}{0.8} (V_{GS1} - 0.6)^2$$

$$V_{GS1} - 0.6 = \sqrt{0.2}$$

$$V_{GS1} = 1.05V$$

$$R = \frac{3 - 1.05}{0.2} = 9.75 k\Omega$$



b) For Q_2 to conduct $0.5mA$:

$$R_2 = \frac{3-1}{0.5} = 4 k\Omega$$

Since the gates are connected together, both transistors have the same V_{GS} and hence same I_D . In order to conduct $0.5mA$

or multiply I_D by 5: $\frac{W_2}{W_1} = 5 \Rightarrow W_2 = 5 \times 8$

$$W_2 = 40 \mu m$$

4.36

Refer to Fig. P4.36.

$$R = \frac{3.5}{0.115} = 3.04 k\Omega$$

$$0.115 = \frac{1}{2} \times 60 \times 10^{-3} \times \frac{W}{0.8} (-1.5 - (-0.7))^2 \Rightarrow W = 4.8 \mu m$$

4.37

Refer to Fig. P4.37

$$V_{GS1} = 1.5V, 120 \mu A = \frac{1}{2} \times 120 \times \frac{W_1}{1} (1.5 - 1)^2$$

$$\Rightarrow W_1 = 8 \mu m$$

$$V_{GS2} = 3.5 - 1.5 = 2V, 120 = \frac{1}{2} \times 120 \times \frac{W_2}{1} (2 - 1)^2$$

$$\Rightarrow W_2 = 2 \mu m$$

$$R = \frac{5 - 3.5}{0.120} = 12.5 k\Omega$$

4.38

Refer to Fig. P4.38.

$$V_{GS1} = 1.5V, 120 \mu A = \frac{1}{2} \times 120 \times \frac{W_1}{1} (1.5 - 1)^2 \Rightarrow W_1 = 8 \mu m$$

$$V_{GS2} = 2V, 120 \mu A = \frac{1}{2} \times 120 \times \frac{W_2}{1} (2 - 1)^2 \Rightarrow W_2 = 2 \mu m$$

$$V_{GS3} = 1.5V, W_3 = 8 \mu m$$

4.39

Refer to Fig. 4.23a. $V_{GS} = 5 - 6I_D \Rightarrow$

$$I_D = \frac{1}{2} \times 2 \times (5 - 6I_D - 2)^2 \Rightarrow 36I_D^2 - 37I_D + 9 = 0$$

$$\Rightarrow I_D = 0.395 mA \text{ or } 0.633 mA$$

$I_D = 0.633 mA$ is not acceptable, because it results in $V_{GS} = 1.2V$ which is lower than $V_t = 2V$.

Therefore $I_D = 0.395 mA \approx 0.4 mA$

$$V_D = 10 - 6I_D = 7.6V$$

These results show that although V_t and $K'_n \frac{W}{L}$ are doubled, I_D is only decreased by 20% and V_D is only increased by 8.5%. Therefore the conclusion is

Cont.

that the circuit is tolerant to changes in device parameters.

4.40

$$V_G = 6V \Rightarrow R_{G1} = 4M\Omega, R_{G2} = 6M\Omega$$

$$I_D = 0.5mA \Rightarrow R_D = \frac{5}{0.5} = 10k\Omega$$

$$I_D = 0.5 = \frac{1}{2} \times 1 \times (V_{GS} + 1.5)^2$$

$$V_{GS} = -2.5V \text{ or } -0.5V$$

($V_{GS} = -0.5V$ is rejected, because it is less than V_P)

$$V_{GS} = -2.5V \Rightarrow V_S = 8.5V \Rightarrow R_S = \frac{10 - 8.5}{0.5} = 3k\Omega$$

4.41

Refer to Fig. P4.41.

$$V_I = V_{GS} = 5V, V_O = V_{DS} = 0.05V$$

$$r_{DS} = 50\Omega = \frac{V_{DS}}{I_D} \Rightarrow I_D = \frac{0.05}{50} = 0.001A = 1mA$$

$$R = \frac{V_{DD} - V_O}{I_D} = \frac{5 - 0.05}{1} = 4.95k\Omega$$

$V_{DS} < V_{GS} - V_P \Rightarrow$ triode region

$$I_D = K'_n \frac{W}{L} \left[(V_{GS} - V_P) V_{DS} - \frac{V_{DS}^2}{2} \right]$$

$$1 = 100 \times 10^{-3} \frac{W}{L} \left[(5 - 1) \times 0.05 - \frac{0.05^2}{2} \right] \Rightarrow \frac{W}{L} = 50$$

4.42

Refer to Fig. P4.42.

in circuit a: $V_2 = 10 - 4 \times 2 = 2V$

assume saturation: $I_D = 2 = \frac{1}{2} \times 1 \times (V_{GS} - 2)^2 \Rightarrow V_{GS} = 4V$
 $\Rightarrow V_1 = -4V, V_{DS} = 6V > V_{GS} - V_P$ So our assumption was correct.

circuit b: $I_D = 1 = \frac{1}{2} \times 1 \times (V_{GS} - 2)^2 \Rightarrow V_{GS} = 3.41V$
 $V_3 = 3.41V$

circuit c: $I_D = 2mA \Rightarrow V_{GS} = -4V \Rightarrow V_5 = 4V = V_4$
 $V_5 = -10 + 2.5 \times 2 = -5V$

In circuit d: $I_D = 2mA \Rightarrow V_{GS} = -4V \Rightarrow V_6 = 6V$
 $\Rightarrow V_7 = V_6 - 4 = 2V$

If we replace the current source with a resistor in each of those circuits:

in circuit a:

$$R = \frac{-4 - (-10)}{2} = 3.01k\Omega \quad (\text{by looking at the table for } \mu\text{ resistors})$$

Now recalculate I_D : $I_D = \frac{1}{2} \times 1 \times (V_{GS} - V_P)^2$
 $V_{GS} - V_P = 0 - (-10 + 3.01I_D) - 2 = 8 - 3.01I_D \Rightarrow$

$$2I_D = (8 - 3.01I_D)^2 \Rightarrow I_D = 1.99mA \Rightarrow V_2 = 2.04V$$

$$V_1 = -4.01V$$

in circuit b:

$$R = \frac{10 - 3.41}{0.99} = 6.59k\Omega \approx 6.65k\Omega$$

Then $V_{GS} = 10 - 6.65I$

$$I = \frac{1}{2} \times 1 \times (10 - 6.65I - 2)^2 \Rightarrow I = 0.99mA$$

$$V_3 = 10 - 6.65 \times 0.99 = 3.41V$$

in circuit c:

$$R = \frac{10 - 4}{2} = 3.01k\Omega, V_{GS} = -(10 - 3.01I)$$

$$I = \frac{1}{2} \times 1 \times (-(10 - 3.01I) + 2)^2 \Rightarrow I_D = 1.99mA$$

$$V_4 = 10 - 3.01 \times 1.99 = 4.01V$$

$$V_5 = -10 + 2.5 \times 1.99 = -5.03V$$

in circuit d:

$$R = \frac{2}{2} = 1k\Omega \text{ so } V_7 \text{ is still } 2V$$

4.43

a) $V_{GS} = -V_1, 10\mu A = \frac{1}{2} \times 0.4 \times 10^{-3} (V_{GS} - 1)^2 \Rightarrow$
 $V_{GS} = 1.22V \Rightarrow V_1 = -1.22V$

b) $100\mu A = \frac{1}{2} \times 0.4 \times 10^{-3} (V_{GS} - 1)^2 \Rightarrow V_{GS} = 1.71V, V_2 = -1.71V$

c) $1 = \frac{1}{2} \times 0.4 \times 10^{-3} (V_{GS} - 1)^2 \Rightarrow V_{GS} = 3.23V \Rightarrow V_3 = -3.23V$

d) $10 = \frac{1}{2} \times 0.4 \times 10^{-3} (V_{GS} - 1)^2 \Rightarrow V_{GS} = 1.22V \Rightarrow V_4 = 1.22V$

e) $1 = \frac{1}{2} \times 0.4 \times 10^{-3} (V_{GS} - V_P)^2 \Rightarrow V_{GS} = 3.24V \Rightarrow V_5 = 3.24V$

f) $I = \frac{1}{2} \times 0.4 \times (5 - 100I - 1)^2 \Rightarrow I = 0.045mA, 0.036mA$

$$V_6 = 5 - 100 \times 0.036 = 1.4V$$

$$g) I = \frac{1}{2} \times 0.4 \times (5 - 1 - I)^2 \Rightarrow I = 1.38 \text{ mA}$$

$$V_g = 5 - 1.38 \times 1 = 3.62 \text{ V}$$

$$h) I = \frac{1}{2} \times 0.4 \times (5 - 100 - I)^2 \Rightarrow I = 0.045 \text{ mA}, 0.036 \text{ mA}$$

$$V_g = -5 + 100 \times 0.036 = -1.4 \text{ V}$$

Note that $I = 0.045 \text{ mA}$ in circuits h and f is not acceptable, because it results in $V_{GS} < V_t$ that is not physically possible.

4.44

Refer to Fig. P4.44.

$$a) V_{GS2} = -V_2, I = \frac{V_2 - (-5)}{1 \text{ k}} = \frac{1}{2} \times 2 \times (-V_2 - 1)^2$$

$$\Rightarrow V_2 + 5 = V_2^2 + 2V_2 + 1 \Rightarrow V_2^2 + V_2 - 4 = 0 \Rightarrow V_2 = 1.55 \text{ V}$$

$$V_2 = -2.56 \text{ V}$$

$V_2 = 1.55 \text{ V}$ is not acceptable because it results in $V_{GS} < 0$ that is not possible for an NMOS.

Therefore $V_2 = -2.56 \text{ V}$

$$i_{D1} = i_{D2} \Rightarrow \frac{V_1 - (-5)}{1 \text{ k}} = \frac{1}{2} \times 2 \times (5 - V_1 - 1)^2$$

$$2.44 = (4 - V_1)^2 \Rightarrow 4 - V_1 = \pm 1.56 \text{ V} \Rightarrow V_1 = 2.44 \text{ V}$$

$$V_1 = 5.56 \text{ V} \times$$

The second answer results in $V_{GS} = 5 - 5.56 < 0$ which is not acceptable. Therefore $V_1 = 2.44 \text{ V}$

$$b) \frac{10 - V_3}{1 \text{ k}} = \frac{V_5}{1 \text{ k}} = i_D \Rightarrow 10 - V_3 = V_5 \quad (1)$$

$$i_{D1} = \frac{V_5}{1 \text{ k}} = \frac{1}{2} \times 2 \times (V_3 - V_4 - 1)^2 \Rightarrow V_5 = (V_3 - V_4 - 1)^2 \quad (2)$$

$$i_{D2} = \frac{V_5}{1 \text{ k}} = \frac{1}{2} \times 2 \times (V_4 - V_5 - 1)^2 \Rightarrow V_5 = (V_4 - V_5 - 1)^2 \quad (3)$$

$$(2), (3) \Rightarrow V_3 - V_4 - 1 = V_4 - V_5 - 1 \Rightarrow V_5 = 2V_4 - V_3 \quad (4)$$

$$(1), (4) \Rightarrow 2V_4 - V_3 = 10 - V_3 \Rightarrow V_4 = 5 \text{ V}$$

$$(3) \Rightarrow V_5 = (4 - V_5)^2 \Rightarrow V_5^2 - 9V_5 + 16 = 0 \Rightarrow V_5 = 6.55 \text{ V}$$

$$V_5 = 2.45 \text{ V}$$

$V_5 = 6.55$ results in $i_D = 6.55 \text{ mA}$, $V_3 = 4.45 \text{ V}$ and this is not physically possible. So $V_5 = 2.45 \text{ V}$

$$V_3 = 10 - 2.45 = 7.55 \text{ V}$$

4.45

The PMOS transistor operates in saturation

region if $V_{SD} > V_{SG} - |V_t|$

or $V_{SD} > V_{SG} - 1$

Also, $V_{SD} + IR = V_{SG} \Rightarrow V_{SD} = V_{SG} - IR$

$\Rightarrow IR \leq |V_t|$ for PMOS to be in saturation.



$$a) R = 0 \Rightarrow IR = 0 < |V_t|$$

saturation:

$$I = 100 = \frac{1}{2} \times 8 \times 25 \times (V_{SG} - |V_t|)^2$$

$$V_{SG} - 1 = \pm 1 \Rightarrow V_{SG} = 2 \text{ V} = V_{SD}$$

$$b) R = 10 \text{ k}\Omega \Rightarrow IR = 10 \times 0.1 = 1 \text{ V} \Rightarrow \text{saturation}$$

$$V_{SG} = 2 \text{ V} \Rightarrow V_{SD} = 2 - 1 = 1 \text{ V}$$

$$c) R = 30 \text{ k}\Omega \Rightarrow IR = 30 \times 0.1 = 3 \text{ V} \Rightarrow \text{triode region}$$

$$100 = 8 \times 25 \left[(V_{SG} - |V_t|) V_{SD} - \frac{1}{2} V_{SD}^2 \right]$$

$$0.5 = [(V_{SG} - 1)(V_{SG} - 3) - \frac{1}{2} (V_{SG} - 3)^2]$$

$$0.5 = 0.5 V_{SG}^2 - V_{SG} - 1.5 \Rightarrow V_{SG}^2 - 2V_{SG} - 4 = 0$$

$$V_{SG} = 3.24 \text{ V}, -1.2 \text{ V} \times$$

$$V_{SD} = 3.24 - 3 = 0.24 \text{ V}$$

$$d) R = 100 \text{ k}\Omega \Rightarrow IR = 100 \times 0.1 = 10 \text{ V} \Rightarrow \text{triode region}$$

$$100 = 8 \times 25 \left[(V_{SG} - 1)(V_{SG} - 10) - \frac{1}{2} (V_{SG} - 10)^2 \right]$$

$$0.5 = 0.5 V_{SG}^2 - V_{SG} - 40 \Rightarrow V_{SG}^2 - 2V_{SG} - 81 = 0$$

$$V_{SG} = 10.1 \text{ V} \Rightarrow V_{SD} = 0.1 \text{ V}$$

$$e) V_{SD} = V_{SG} \text{ when } R = 0$$

f) $V_{SD} = V_{SG}/2$ For the device in saturation, $V_{SG} = 2 \text{ V}$ (for $I = 100 \mu\text{A}$), therefore $V_{SD} = \frac{V_{SG}}{2} = 1 \text{ V}$ implies: $IR = 1 \text{ V} \Rightarrow R = 10 \text{ k}\Omega$

$$g) V_{SD} = \frac{V_{SG}}{10} \text{ In saturation: } V_{SG} = 2 \text{ V}, V_{SD} = 0.2 \text{ V}$$

$$\Rightarrow V_{SD} < V_{SG} - |V_t| \Rightarrow \text{therefore}$$

the device can't be in saturation and it is in

triode region: $100 = \frac{1}{2} \times 8 \times 25 \left[(V_{SG} - 1) \left(\frac{V_{SG}}{10} \right) - \frac{1}{2} \left(\frac{V_{SG}}{10} \right)^2 \right]$

$$0.5 = \frac{V_{SG}^2}{10} - \frac{V_{SG}^2}{200} - 0.1 V_{SG} \Rightarrow 19 V_{SG}^2 - 20 V_{GS} - 100 = 0$$

$$\Rightarrow V_{SG} = 2.88 \text{ V}, -1.82 \text{ V} \times$$

$$V_{SD} = \frac{2.88}{10} = 0.288 \text{ V} \Rightarrow IR = 2.88 - 0.288 = 2.59 \text{ V}$$

$$\Rightarrow R = 25.9 \text{ k}\Omega$$

4.46

a) Q_2, Q_1 operating in Saturation: $i_{D1} = i_{D2}$

$$\Rightarrow V_{GS1} = V_{GS2}$$

$$3V = V_{GS1} + V_{GS2} \Rightarrow V_{GS1} = V_{GS2} = 1.5V$$

$$I_1 = \frac{1}{2} \times 20 \times \frac{30}{10} (1.5 - 1)^2 = 7.5 \mu A$$



b) Both transistors have $V_D = V_G$ and therefore they are operating in Saturation: $i_{D1} = i_{D2}$

$$\frac{1}{2} \mu_n C_{ox} \frac{W_1}{L_1} (V_1 - 1)^2 = \frac{1}{2} \mu_n C_{ox} \frac{W_2}{L_2} (V_2 - 1)^2$$

$$2.5 (V_1 - 1)^2 = (V_2 - 1)^2$$

$$1.58 (V_1 - 1) = (V_2 - 1) \Rightarrow V_2 = 1.39 V \approx 1.4 V$$

$$I_3 = \frac{1}{2} \times 20 \times \frac{30}{10} (1.39 - 1)^2 = 4.6 \mu A$$



$$c) \frac{W_1}{L_1} = \frac{75}{10} = 7.5$$

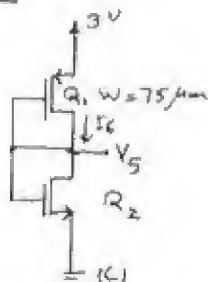
$$\frac{W_2}{L_2} = \frac{30}{10} = 3 \quad \frac{W_1}{L_1} = 2.5$$

$$i_{D1} = i_{D2}$$

$$\text{Since } \mu_n C_{ox} \frac{W_1}{L_1} = \mu_n C_{ox} \frac{W_2}{L_2}$$

$$\Rightarrow V_{GS1} = V_{GS2} = \frac{3}{2} = 1.5V = V_5$$

$$I_6 = \frac{1}{2} \times 20 \times \frac{30}{10} (1.5 - 1)^2 = 7.5 \mu A$$



4.47

Refer to Fig. P4.47.

Since $V_{G1} = V_{D1}$, then Q_1 is in saturation. We assume that Q_2 is also in saturation, then

because $i_{D1} = i_{D2}$, V_{GS1} would be equal to V_{GS2} .

$$V_{GS1} = V_{GS2} = \frac{5}{2} = 2.5V$$

$$I_1 = \frac{1}{2} \times 50 \times \frac{10}{1} (2.5 - 1)^2 = 562.5 \mu A$$

$V_{GS3} = V_{GS1} = 2.5V$. Since Q_3 and Q_4 have the same drain current, then $V_{GS3} = V_{GS4} = 2.5V$.

This is based on the assumption that Q_3 & Q_4 are saturated:

$$V_{GS3} = V_{GS1} \Rightarrow I_2 = I_{GS3} = I_{GS1} = 562.5 \mu A$$

$$V_2 = 5 - 2.5 = 2.5V$$

Now if Q_3 and Q_4 have $W = 100 \mu m$ then:

$$I_2 = \frac{1}{2} \times 50 \times \frac{100}{1} (2.5 - 1)^2 = 5.625 mA \quad \text{or}$$

$$\frac{I_{Q3}}{I_{Q1}} = \frac{W_3}{W_1} = \frac{100}{10} \Rightarrow I_{Q3} = 10 \times 562.5 \mu A = 5.625 mA$$

4.48

$$a) \left(\frac{W}{L}\right)_1 = \left(\frac{W}{L}\right)_2 = 20$$

$$V_{GS1} = V_{GS2} = -V_3$$

Assuming that the transistors are in saturation, since K'_n and $\frac{W}{L}$ are the same for both Q_2 and Q_1 , we can write:

$$i_{D1} = i_{D2} = \frac{100}{2} = 50 \mu A$$

$$100 \mu A = \frac{1}{2} \times 100 \times 20 \times (V_{GS} - 1)^2 \Rightarrow 0.1 = (V_{GS} - 1)^2$$

$$V_{GS} = 1.32V = -V_3 \Rightarrow V_3 = -1.32V$$

$$V_1 = 5 - 40 \times 100 \mu A = 1V \quad V_2 = 1V$$

$$b) \left(\frac{W}{L}\right)_1 = \left(\frac{W}{L}\right)_2 \times 1.5 = 20 \quad \text{assume } Q_3, Q_4 \text{ are saturated:}$$

$$V_{GS1} = V_{GS2} = -V_3 \Rightarrow i_{D1} = \left(\frac{W}{L}\right)_1 \times 1.5$$

$$i_{D1} = 1.5 i_{D2} \quad i_{D1} + i_{D2} = 0.2 mA \Rightarrow i_{D1} = 120 \mu A, i_{D2} = 80 \mu A$$

$$i_{D1} = 120 = \frac{1}{2} \times 100 \times 20 \times (V_{GS1} - 1)^2 \Rightarrow V_{GS1} = 1.35V$$

$$\Rightarrow V_3 = -1.35V$$

$$V_1 = 5 - 40 \times 0.12 = 0.2V, V_2 = 5 - 40 \times 0.08 = 1.8V$$

$$V_{GS1} = 0.2 + 1.35 = 1.55V > V_{GS} - 1$$

$$V_{GS2} = 1.8 + 1.35 = 3.15V > V_{GS} - 1$$

This confirms that both transistors are indeed saturated and our assumption was correct.

4.49

a)

$$\text{Point A: } V_{GS} = V_{th} = 1V, V_{DS} = V_{DD} = 5V$$

For $V_i < V_{th}$, the transistor is not on, $V_{GS} < V_{th}$.

Point A is when $V_{GS} = V_{th}$ and the transistor turns on. As V_i increases, the i_D increases and V_o decreases.

V_o decreases to the point that it is below V_{th} by V_{th} volts. At this point, B, the MOSFET enters the triode region: $V_{GS} = V_{th} - V_{th}$

or $V_{GS} = V_{th} - V_{th}$. So at point B: $I = \frac{V_{DD} - V_{th}}{R}$

$$I = \frac{V_{DD} - V_{th}}{R} = \frac{1}{2} \times K'_n \frac{W}{L} (V_{GS} - V_{th})^2$$

$$\frac{5 - V_{th}}{24} = \frac{1}{2} \times 1 \times (V_{GS} - 1)^2 \Rightarrow 12V_{GS}^2 - 23V_{GS} + 6 = 0$$

Cont.

$$V_{GS} = 1.61V \Rightarrow V_T = 1.61V \quad V_O = 1.61 - 1 = 0.61V$$

Point B: $V_{OB} = 0.61V \quad V_{SB} = 1.61V$

$$b) \quad I_Q = \frac{1}{2} \times 1 \times 0.5^2 = 0.125mA$$

$$V_{OQ} = 5 - 24 \times 0.125 = 2V$$

$$V_{SQ} = V_{GS} = V_{OV} + V_t = 0.5 + 1 = 1.5V$$

Now to calculate the incremental gain

A_v at this bias point, From equation 4.41

$$\text{we have: } A_v = -2 V_{RD} / V_{OV} = -2(V_{DD} - V_{OQ}) / V_{OV}$$

$$A_v = -2(5-2) / 0.5 = -12 V/V$$

c) $V_{SQ} = 1.5V, V_t = 1V, V_{SB} = 1.61V$. Thus the largest amplitude of a sine wave that can be applied to the input while the transistor remains in saturation is: $1.61 - 1.5 = 0.11V$

The amplitude of the output voltage signal that results is approximately equal to $V_{OQ} - V_{OB} = 2 - 0.61 = 1.39V$. The gain implied by this amplitudes is: $\text{gain} = \frac{-1.39}{0.11} = -12.64 V/V$

This gain is 5.3% different from the incremental gain calculated in part (b). This difference is due to the fact that the segment of the voltage transfer curve considered here is not perfectly linear.

4.50

$$V_{DS} = 1V = V_{OQ} \Rightarrow I_D = \frac{V_{DD} - V_{OQ}}{R_D} = \frac{10 - 1}{18} = 0.5mA$$

$$I_D = 0.5 = \frac{1}{2} \times 1 \times V_{OV}^2 \Rightarrow V_{OV} = \sqrt{2I_D} = 1V$$

$$V_{OV} = V_{GS} - V_t \Rightarrow V_{GS} = 2V$$

$$A_v = \frac{-2 V_{RD}}{V_{OV}} = \frac{-2 \times 18 \times 0.5}{1} = -18 V/V$$

$$V_o^+ = V_{DD} - V_{OQ} = 10 - 1 = 9V$$

$$V_o^- = V_{OQ} - V_{OB}$$

In order to find V_{OB} where $V_{DS} = V_{GS} - V_t$ or

$$V_{OB} = V_{SB} - V_t : V_o = V_{DD} - R_D I_D$$

$$V_{OB} = 10 - 18 \times \frac{1}{2} \times 1 \times V_{OB}^2 \Rightarrow 9V_{OB}^2 + V_{OB} - 10 = 0 \Rightarrow V_{OB} = 1V$$

$$V_o^- = V_{OQ} - V_{OB} = 1 - 1 = 0$$

Using the same formulas we can calculate the

rest of the values for $V_{DS} = 2, 3, \dots, 10V$

V_{DS} (V)	I_D (mA)	V_{OV} (V)	V_{GS} (V)	A_v (V/V)	V_o^+ (V)	V_o^- (V)
1	0.5	1	2	18	9	0
2	0.44	0.94	1.94	17.02	8	1
3	0.39	0.88	1.88	15.9	7	2
4	0.33	0.81	1.81	14.8	6	3
5	0.28	0.75	1.75	13.3	5	4
6	0.22	0.66	1.66	12.1	4	5
7	0.17	0.58	1.58	10.3	3	6
8	0.11	0.47	1.47	8.5	2	7
9	0.06	0.35	1.35	5.7	1	8
10	0	0	$\leq 1V$	0	0	9

4.51

$$R_D = 20k\Omega, V_{RD} = 2V \Rightarrow I_D = 0.1mA$$

$$A_v = -\frac{2 V_{RD}}{V_{OV}} \Rightarrow -10 = -\frac{2 \times 2}{V_{OV}} \Rightarrow V_{OV} = 0.4V$$

$$V_{GS} = 1.2V \Rightarrow V_t = 1.2 - 0.4 = 0.8V$$

$$I_D = \frac{1}{2} K_n' \frac{W}{L} V_{OV}^2 \Rightarrow 0.1 = \frac{1}{2} \times 50 \times 10^{-3} \frac{W}{L} 0.4^2$$

$$\Rightarrow \frac{W}{L} = 25$$

4.52

$$\text{Eq. 4.41: } A_v = -\frac{2(V_{DD} - V_{OQ})}{V_{OV}}$$

$$a) A_{vmax} = -\frac{2(V_{DD} - 0)}{V_{OVmin}} = -\frac{2 \times 5}{0.2} = -50 V/V$$

b)

c)

4.53

From Figure 4.26(c) we have: $\hat{V}_o = V_{DS} - V_{DS}$
Assuming linear operation around the bias point:

$$A_v = -\frac{\hat{V}_o}{V_{GS} - V_{GS}} = -\frac{\hat{V}_o}{V_{GS} + V_t - V_{GS}} = -\frac{\hat{V}_o}{V_{GS} + V_t - (V_{GS} + V_t)}$$

$$A_v = -\frac{\hat{V}_o}{V_{GS} - V_{GS}} = -\frac{\hat{V}_o}{V_{GS} - V_{GS} + V_{GS} - V_{GS}} = -\frac{\hat{V}_o}{-V_{GS} + V_{GS} - V_{GS}}$$

$$-A_v \hat{V}_o + A_v (V_{DS} - V_{GS}) = -\hat{V}_o \Rightarrow \hat{V}_o (1 - A_v) = -A_v (V_{DS} - V_{GS})$$

$$\hat{V}_o = \frac{A_v (V_{DS} - V_{GS})}{1 - A_v} \Rightarrow \hat{V}_o = \frac{V_{DS} - V_{GS}}{1 - \frac{1}{A_v}}$$

V_{DS} (V)	A_v (%)	\hat{V}_o (V)	\hat{V}_i (V)
1	-16	0.47	0.029
1.5	-14	0.93	0.065
2	-12	1.38	0.12
2.5	-10	1.81	0.18

$$I_D = \frac{1}{2} \times 1 \times (0.5)^2 = 0.125 \text{ mA}$$

$$R_D = \frac{V_{DD} - V_{DS}}{I_D} = \frac{5 - 1}{0.125} = 32 \text{ k}\Omega$$

4.54

$$i_{D1} = i_{D2} \Rightarrow \frac{1}{2} K_n \left(\frac{W}{L}\right)_1 (V_{GS1} - V_t)^2 = \frac{1}{2} K_n \left(\frac{W}{L}\right)_2 (V_{GS2} - V_t)^2$$

$$\text{Note that } V_{GS1} = V_t$$

$$V_{GS2} = V_{DD} - V_o$$

$$\Rightarrow \left(\frac{W}{L}\right)_1 (V_t - V_t)^2 = \left(\frac{W}{L}\right)_2 (V_{DD} - V_o - V_t)^2$$

$$\sqrt{\left(\frac{W}{L}\right)_1} / \sqrt{\left(\frac{W}{L}\right)_2} (V_t - V_t) = V_{DD} - V_o - V_t$$

$$V_o = V_{DD} - V_t + \sqrt{\frac{(W/L)_1}{(W/L)_2}} V_t - \sqrt{\frac{(W/L)_1}{(W/L)_2}} V_t$$

$$\text{If } \left(\frac{W}{L}\right)_1 = \frac{50}{0.5} = 100 \quad \left(\frac{W}{L}\right)_2 = \frac{5}{0.5} = 10$$

then:

$$A_v = \frac{\partial V_o}{\partial V_i} = -\sqrt{\frac{100}{10}} = -3.16 \text{ V/V}$$

4.55

$$I_D = 2 \text{ mA} = \frac{1}{2} \times 80 \times 10^{-3} \times \frac{240}{6} \times (V_{GS} - 1.2)^2 \Rightarrow$$

$$V_{GS} = 2.32 \text{ V} \quad \text{Refer to Fig. 4.30c}$$

$$R_D I_D = \frac{15}{3} = 5 \text{ V} \Rightarrow R_D = \frac{5}{2 \text{ mA}} = 2.5 \text{ k}\Omega$$

$$R_S I_D = 5 \text{ V} \Rightarrow R_S = \frac{5}{2} = 2.5 \text{ k}\Omega$$

$$V_G = 5 + V_{GS} = 7.32 \text{ V}$$

$$\frac{15}{R_{G1} + R_{G2}} \times R_{G2} = 7.32 \quad R_{G1} = 22 \text{ M}\Omega \Rightarrow R_{G2} = 20.97 \text{ M}\Omega$$

$$V_{DS} = 5 \text{ V}$$

at the edge of saturation $V_{DS} = V_{GS} - V_t$ or

$$V_{DS} = 2.32 - 1.2 = 1.12 \text{ V}. \text{ So } V_{DS} \text{ is } 5 - 1.12 = 3.88 \text{ V}$$

away from the edge of saturation.

4.56

Refer to Fig. 4.30e

$$I_D = 2 \text{ mA} = \frac{1}{2} K_n' \frac{W}{L} V_{GS}^2 \Rightarrow 2 = \frac{1}{2} \times 50 \times 10 \times \frac{200}{4} V_{GS}^2$$

$$V_{GS} = 1.26 \text{ V}$$

$V_{DS} = V_{GS}$ edge of triode

Midway of cutoff ($V_{DS} = V_{DD}$) and beginning of

triode operation ($V_{DS} = V_{GS}$) is when $V_{DS} = \frac{30 + 1.26}{2}$

$$V_{DS} = 15.63 \text{ V}$$

$$V_{GS} = 2.32 \text{ V} \Rightarrow V_S = -2.32 \text{ V} \Rightarrow R_S = \frac{-2.32 + 15}{2}$$

$$R_S = 6.34 \text{ k}\Omega$$

$$V_D = V_S + V_{DS} = -2.32 + 15.63 = 13.31 \text{ V} \Rightarrow R_D = \frac{15 - 13.31}{2}$$

$$R_D = 0.85 \text{ k}\Omega$$

4.57

$$V_G = 12 \times \frac{2.2}{2.2 + 5.6} = 3.4 \text{ V}$$

$$K_n' \frac{W}{L} = 220 \text{ to } 380 \text{ } \mu\text{A/V}^2$$

$$V_t = 1.3 \text{ to } 2.4 \text{ V}$$

$$I_D = \frac{1}{2} \times K_n' \frac{W}{L} (3.4 - V_t)^2$$

$$I_{Dmin} = \frac{1}{2} \times 220 (3.4 - 2.4)^2 = 110 \text{ } \mu\text{A}$$

$$I_{Dmax} = \frac{1}{2} \times 380 (3.4 - 1.3)^2 = 838 \text{ } \mu\text{A}$$

to limit I_{Dmax} to $150 \text{ } \mu\text{A}$:

$$150 = \frac{1}{2} \times 380 (3.4 - 0.15 R_S - 1.3)^2$$

$$R_S = 8.1 \text{ k}\Omega$$

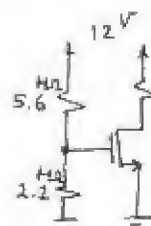
$$\text{Select } R_S = 8.2 \text{ k}\Omega$$

$$I_{Dmax} = \frac{1}{2} \times 380 (3.4 - I_{Dmax} \times 8.2 - 1.3)^2$$

$$I_{Dmax} = 0.15 \text{ mA or } 0.3 \text{ mA}$$

The second answer results in negative V_{GS}

Cont.



and therefore it is not acceptable.

$$I_{Dmin} = \frac{1}{2} \times 0.22 \times (3.4 - 8.2 I_{Dmin} - 2.4)^2$$

$$I_{Dmin} = 0.04 \text{ mA}$$

4.58

$$V_t = 2 \text{ V}, K'_n \frac{W}{L} = 2 \text{ mA/V}^2$$

$$I_D = \frac{1}{2} \times 2 \times (4 - I_D \times 1 - 2)^2$$

$$I_D = 4 + I_D^2 - 4I_D \Rightarrow I_D = 1 \text{ mA}$$

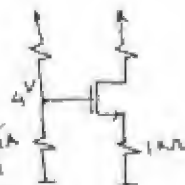
$I_D = 4 \text{ mA}$ results in $V_{GS} = 0$ which

is not acceptable, therefore $I_D = 1 \text{ mA}$.

For $K'_n \frac{W}{L}$ 50% larger, i.e. $K'_n \frac{W}{L} = 3 \text{ mA/V}^2$

$$I_D = \frac{1}{2} \times 3 \times (4 - I_D - 2)^2 \Rightarrow I_D = 1.13 \text{ mA}$$

I_D increases by 13%.



4.59

Refer to Fig. 4.30.c

$$V_{GS} = 5 - 2 = 3 \text{ V} \Rightarrow I_D = \frac{V_S}{R_S} = \frac{2}{1} = 2 \text{ mA}$$

$$I_D = 2 = \frac{1}{2} \times 2 \times (3 - V_t)^2 \Rightarrow 1.41 = 3 - V_t \Rightarrow V_t = 1.59 \text{ V}$$

For a device with $V_t = 1.59 - 0.5 = 1.09 \text{ V}$:

$$I_D = \frac{1}{2} \times 2 \times (5 - I_D \times 1 - 1.09)^2 \Rightarrow I_D = 2.37 \text{ mA}$$

$$V_S = 2.37 \text{ V}$$

4.60

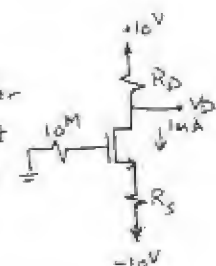
To maximize gain, we design for the lowest possible V_D consistent with allowing a 2V p-p signal swing. $V_{Dmin} = V_D - 1$

$$V_{Dmin} = V_G - V_t = 0 - 2$$

$$V_D - 1 = -2 \Rightarrow V_D = -1 \text{ V} \Rightarrow R_D = \frac{10 - (-1)}{1 \text{ mA}} = 11 \text{ k}\Omega$$

$$I_D = \frac{1}{2} \times 2 \times [0 - (-10 + 1 \times R_S) - 2]^2 = 1 \Rightarrow 1 = (8 - R_S)^2$$

$$R_S = 7 \text{ k}\Omega$$



4.61

For p-channel MOSFET to be 1V from the edge of saturation: $V_{DS} = V_{GS} - V_t - 1$. Since $V_D = 3 \text{ V}$

$$\text{and } I_D = 1 \text{ mA: } R_D = \frac{3}{1} = 3 \text{ k}\Omega, R_1 + R_2 = \frac{10 \text{ V}}{10 \mu\text{A}} = 1 \text{ M}\Omega$$

$$a) V_{GS} = 1 \text{ V}, K'_p \frac{W}{L} = 0.5 \text{ mA/V}^2$$

$$I_D = 0.5 \times \frac{1}{2} \times (V_{GS} + 1)^2 = 1 \Rightarrow V_{GS} = -3 \text{ V}$$

$$V_{DS} = -3 + 1 - 1 = -3 \text{ V}$$

$$V_S = 6 \text{ V}, V_G = 3 \text{ V}, R_3 = \frac{10 - 6}{1} = 4 \text{ k}\Omega$$

$$\frac{R_2}{R_1 + R_2} = \frac{3}{10} \Rightarrow R_1 = 0.7 \text{ M}\Omega, R_2 = 0.3 \text{ M}\Omega$$

$$b) V_{GS} = 2 \text{ V}, K'_p \frac{W}{L} = 1.25 \text{ mA/V}^2$$

$$1 = \frac{1}{2} \times 1.25 (V_{GS} + 2)^2 \Rightarrow V_{GS} = -3.26 \text{ V or } -0.74 \text{ V}$$

the second answer is not acceptable $|V_{GS}| > |V_t|$

$$V_{GS} = -3.26 \text{ V}$$

$$V_{DS} = -3.26 + 2 - 1 = -2.26 \text{ V}$$

$$V_S = 3 + 2.26 = 5.26 \text{ V}$$

$$V_G = 2 \text{ V}$$

$$R_3 = \frac{10 - 5.26}{1} = 4.74 \text{ k}\Omega, R_D = 3 \text{ k}\Omega$$

$$\frac{R_2}{R_1 + R_2} = \frac{2}{10} \Rightarrow R_2 = 0.2 \text{ M}\Omega, R_1 = 0.8 \text{ M}\Omega$$

4.62

$$K = \frac{1}{2} K'_n \frac{W}{L}$$

$$a) I_D = \frac{1}{2} K'_n \frac{W}{L} (V_{GS} - V_t)^2$$

$$I_D = K (V_{GS} - V_t)^2$$

$$\frac{\partial I_D}{\partial K} = (V_{GS} - V_t)^2 + 2K(V_{GS} - V_t)(V_t) \frac{\partial V_t}{\partial K}$$

$$\frac{\partial I_D}{\partial K} = \frac{I_D}{K} - 2R_S \sqrt{\frac{I_D}{K}} \times \frac{\partial I_D}{\partial K}$$

$$\frac{\partial I_D}{\partial K} (1 + 2\sqrt{K I_D} R_S) = \frac{I_D}{K} \Rightarrow S_{I_D}^K = \frac{\partial I_D}{\partial K} \frac{K}{I_D} = \frac{1}{1 + 2\sqrt{K I_D} R_S}$$

$$b) K = 100 \mu\text{A/V}^2, \frac{\Delta K}{K} = \pm 10\%, V_t = 1 \text{ V}, I_D = 100 \mu\text{A}$$

$$\frac{\Delta I_D}{I_D} = \pm 1\%$$

$$S_{I_D}^K = \frac{\partial I_D / I_D}{\partial K / K} = \frac{1}{10} = 0.1 = \frac{1}{1 + 2\sqrt{100 \times 10^{-6} \times 100 \times 10^{-3}} R_S}$$

$$\Rightarrow R_S = 45 \text{ k}\Omega$$

Cont.

$$100 = 100 (V_{GS} - 1)^2 \Rightarrow V_{GS} = 2V$$

$$V_{GS} = V_{SS} - I_D R_S \Rightarrow 2 = V_{SS} - 0.1 \times 45 \Rightarrow V_{SS} = 6.5V$$

c) For $V_{SS} = 5V$:

$$R_S = \frac{-V_{GS} + V_{SS}}{I_D} = \frac{-2 + 5}{0.1} = 30k\Omega$$

$$S_{I_D} = \frac{1}{1 + 2\sqrt{0.1 \times 0.1} \times 30} = \frac{1}{1 + 2 \times 0.1 \times 30} = 0.14$$

Therefore for $\frac{\Delta K}{K} = 10\%$, $\frac{\Delta I_D}{I_D} = 1.4\%$

4.63

Both cases are in saturation region, because

$$V_{DG} > V_t$$

$$V_D = 10 - 5 \times 1 = 5V$$

$$a) 1 = \frac{1}{2} \times 0.5 \times (V_{GS} - 1)^2 \Rightarrow V_{GS} = 3V, V_S = -3V$$

$$V_{DS} = 8V$$

$$b) 1 = \frac{1}{2} \times 1.25 \times (V_{GS} - 2)^2 \Rightarrow V_{GS} = 3.3V, V_S = -3.3V$$

$$V_{DS} = 8.3V$$

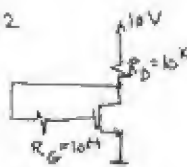
4.64

$$V_D = V_G = V_{GS} \text{ Refer to Fig. 4.32}$$

to operate in saturation:

$$V_{DS} \geq V_{GS} - V_t \Rightarrow V_{DG} \geq -V_t$$

$$V_{DG} = 0$$



$$a) \frac{10 - V_D}{10} = \frac{1}{2} \times 0.5 \times (V_D - 1)^2 \Rightarrow V_D = 2.7V$$

$$V_G = 2.7V$$

$$b) \frac{10 - V_D}{10} = \frac{1}{2} \times 1.25 \times (V_D - 2)^2 \Rightarrow V_D = 3.05V$$

$$V_G = 3.05V$$

4.65

For $I_D = 0.2mA$:

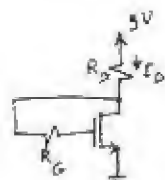
$$0.2 = \frac{1}{2} \times 0.4 \times (V_{GS} - 1)^2$$

$$V_{GS} = 2V, V_D = V_G = V_{GS} = 2V$$

$$R_D = \frac{9 - 2}{0.2} = 35k\Omega$$

$$\text{Select } R_D = 36k\Omega \Rightarrow \frac{9 - V_D}{R_D} = \frac{1}{2} \times 0.4 \times (V_D - 1)^2$$

$$\frac{9 - V_D}{36} = 0.2 (V_D - 1)^2 \Rightarrow V_D = 2V, I_D = 0.2mA$$



4.66

$$I_D = 2 = \frac{1}{2} \times 3.2 \times (V_{GS} - 1.2)^2$$

$$V_{GS} - 1.2 = 1.12 \Rightarrow V_{GS} = 2.32V$$

$$V_G = 2.32V$$

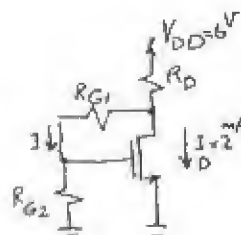
$$V_{DSmin} = V_{GS} - V_t = 1.12V$$

$$V_{DS} = V_{DSmin} + 2 = 3.12V$$

$$R_{G2} = 22M\Omega \Rightarrow I = \frac{2.32}{22} = 0.11\mu A$$

$$R_{G1} = \frac{3.12 - 2.32}{0.11} = 7.58M\Omega$$

$$R_D = \frac{6 - 3.12}{2 \times 0.11 \times 10^{-3}} = 1.44k\Omega$$



4.67

Eq. 4.57 implies:

$$i_D = I_D + K'_n \frac{W}{L} (V_{GS} - V_t) V_{GS} \sin \omega t + \frac{1}{2} K'_n \frac{W}{L} V_{GS}^2 \sin^2 \omega t$$

$$i_D = I_D + K'_n \frac{W}{L} (V_{GS} - V_t) V_{GS} \sin \omega t + \frac{1}{2} K'_n \frac{W}{L} V_{GS}^2 \left(\frac{1 - \cos 2\omega t}{2} \right)$$

$$i_D = I_D + K'_n \frac{W}{L} (V_{GS} - V_t) V_{GS} \sin \omega t + \frac{1}{4} K'_n \frac{W}{L} V_{GS}^2 - \frac{V_{GS}^2}{4} K'_n \frac{W}{L} \cos 2\omega t$$

$$\text{Second Harmonic Distortion} = \frac{\frac{1}{4} K'_n \frac{W}{L} V_{GS}^2}{K'_n \frac{W}{L} (V_{GS} - V_t) V_{GS}} \times 100$$

$$= \frac{1}{4} \frac{V_{GS}}{V_{GS} - V_t} \times 100$$

$$\text{Second Harmonic Distortion} = \frac{1}{4} \frac{V_{GS}}{V_{OV}} \times 100$$

$$\text{For } V_{GS} = 10mV, \frac{1}{4} \times \frac{10 \times 10^{-3}}{V_{OV}} \times 100 \leq 1$$

$$\Rightarrow V_{OV} \geq 0.25V \Rightarrow V_{OVmin} = 0.25V$$

4.68

$$I_D = \frac{1}{2} K'_n \frac{W}{L} V_{OV}^2 \Rightarrow I_D = \frac{1}{2} \times 2 \times 1^2 = 1mA$$

$$I_D = \frac{1}{2} \times 2 \times (1 + 0.1)^2 = 1.21mA \quad (V_{GS} = 0.1V)$$

$$I_D = 1.21 - 1 = 0.21mA$$

$$\text{If } V_{GS} = -0.1V \Rightarrow I_D = \frac{1}{2} \times 2 \times (1 - 0.1)^2 = 0.81mA$$

$$I_D = 0.81 - 1 = -0.19mA$$

$$\text{For positive increment: } g_m = \frac{\Delta I_D}{\Delta V_{GS}} = \frac{0.21}{0.1} = 2.1mA/V$$

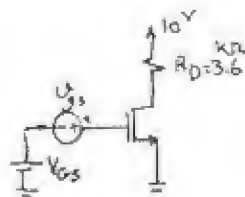
$$\text{For negative increment: } g_m = \frac{0.19}{0.1} = 1.9mA/V$$

$$\text{An estimate of } g_m = \frac{2.1 + 1.9}{2} = 2mA/V$$

$$\text{Eq. 4.62 } g_m = K'_n \frac{W}{L} V_{OV} = 2 \times 1 = 2mA/V \text{ same as estimate!}$$

4.69

$$\begin{aligned} a) I_D &= \frac{1}{2} \times 1 \times (4-2)^2 = 2 \text{ mA} \\ V_D &= V_{DD} - R_D I_D = 10 - 2 \times 3.6 \\ V_D &= 2.8 \text{ V} \end{aligned}$$



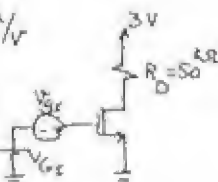
$$\begin{aligned} b) g_m &= k'_n \frac{W}{L} V_{OV} = 1 \times (4-2) = 2 \text{ mA/V} \\ c) A_v &= \frac{V_D}{V_{GS}} = -g_m R_D = -2 \times 3.6 = -7.2 \text{ V/V} \end{aligned}$$

$$\begin{aligned} d) r_o &\approx \frac{1}{\lambda I_D} = \frac{1}{0.01 \times 2} = 50 \text{ k}\Omega \\ A_v &= \frac{V_D}{V_{GS}} = -g_m (R_D \parallel r_o) = -2(3.6 \parallel 50) = -6.7 \text{ V/V} \end{aligned}$$

4.70

$$g_m R_D = 5 \Rightarrow g_m = \frac{5}{50} = 0.1 \text{ mA/V}$$

For 0.5V output signal and a gain of 5V/V, $V_{GS} = \frac{0.5}{5} = 0.1 \text{ V}$



So we can write $V_{DS} = 0.5 \geq V_{GS} + 0.1 - V_t$
 or $V_{DS} \geq V_{GS} + 0.6 - 0.8 \Rightarrow V_{DS} \geq V_{GS} - 0.2$
 Also, from the other side: $V_{DS} + 0.5 \leq V_{DD}$
 or $V_{DS} \leq 3 - 0.5 \Rightarrow V_{DS} \leq 2.5 \text{ V}$

We design the circuit for lowest possible V_{DS} that guarantees the device operation in saturation: $V_{DS} = V_{GS} - 0.2$

$$\begin{aligned} V_{DS} &= V_{DD} - R_D I_D \Rightarrow V_{GS} - 0.2 = 3 - 50 \times I_D \\ \Rightarrow I_D &= \frac{3.2 - V_{GS}}{50} \end{aligned}$$

$$\text{Also, from eq. 4.71: } g_m = \frac{2 I_D}{V_{GS} - V_t} = 0.1$$

$$0.1 = \frac{2}{V_{GS} - 0.8} \times \frac{3.2 - V_{GS}}{50}$$

$$\Rightarrow V_{GS} = 1.49 \text{ V} \quad I_D = 0.034 \text{ mA}$$

$$V_{DS} = 1.49 - 0.2 = 1.29 \text{ V} \quad V_{OV} = 1.49 - 0.8 = 0.69 \text{ V}$$

$$\frac{W}{L} = \frac{I_D}{\frac{1}{2} k'_n V_{OV}^2} = \frac{0.034 \times 10^{-3}}{\frac{1}{2} \times 100 \times 0.69^2} = 1.43$$

$$\frac{W}{L} = 1.43$$

4.71

$$\begin{aligned} A_v &= -g_m R_D \\ g_m &= \frac{2 I_D}{V_{OV}} \quad \text{eq. 4.71} \end{aligned} \Rightarrow A_v = -\frac{2 R_D I_D}{V_{OV}} = -2 \frac{(V_{DD} - V_D)}{V_{OV}} \quad (1)$$

Minimum V_{DS} for edge of saturation:

$$V_{DS} \geq V_{GS} - V_t \quad \text{or } V_{DSmin} = V_{GSmax} - V_t$$

$$V_{DS} - |A_v| \hat{V}_i = V_{GS} + \hat{V}_i - V_t$$

If we replace A_v with (1),

$$V_D - \frac{2(V_{DD} - V_D)}{V_{OV}} \hat{V}_i = V_{GS} + \hat{V}_i$$

$$\Rightarrow V_D (1 + \frac{2 \hat{V}_i}{V_{OV}}) = V_{OV} + \hat{V}_i + \frac{2 V_{DD} \hat{V}_i}{V_{OV}}$$

$$V_D = \frac{V_{OV} + \hat{V}_i + 2 V_{DD} (\hat{V}_i / V_{OV})}{1 + 2 (\hat{V}_i / V_{OV})}$$

$$V_{DD} = 3 \text{ V}, \hat{V}_i = 20 \text{ mV} \quad m = 10 = \frac{V_{OV}}{V_{OV}} \Rightarrow V_{OV} = 0.2 \text{ V}$$

$$V_D = \frac{0.2 + 0.02 + 2 \times 3 \times 0.02}{1 + 2 \times 0.1} = 0.68 \text{ V}$$

$$A_v = \frac{2(3 - 0.68)}{0.2} = -23.2 \text{ V/V}$$

If $I_D = 100 \mu\text{A} = 0.1 \text{ mA}$:

$$A_v = -\frac{2 R_D I_D}{V_{OV}} \Rightarrow 23.2 = \frac{2 \times R_D \times 0.1}{0.2} \Rightarrow$$

$$R_D = 23.2 \text{ k}\Omega$$

$$I_D = \frac{1}{2} k'_n \frac{W}{L} V_{OV}^2 \Rightarrow 0.1 = \frac{1}{2} \times 100 \times 10 \frac{W}{L} \times 0.2^2$$

$$\Rightarrow \frac{W}{L} = 50$$

4.72

$$k'_n = \mu_n C_{ox} = 500 \times 10^{-8} \times 0.4 \times 10^{15} = 20 \text{ mA/V}^2, \quad k'_p = 10 \text{ mA/V}^2$$

Case	Type	I_D (mA)	$ V_{GS} $ (V)	$ V_t $ (V)	V_{OV} (V)	W (μm)	L (μm)	$\frac{W}{L}$ (μm/μm)	$\frac{W}{L}$ (μm/μm)	g_m (mA/V)
a	N	1	3	2	1	100	1	100	2	2
b	N	1	1.2	0.7	0.5	50	$\frac{1}{8}$	400	8	4
c	N	10	?	?	2	250	1	250	5	10
d	N	0.5	?	?	0.5	?	?	200	4	2
e	N	0.1	?	?	1.41	10	2	5	0.1	0.14
f	N	0.1	1.8	0.8	1	40	4	10	0.2	0.2
g	P	1	?	?	2	?	?	25	0.25	1
h	P	1	3	1	2	?	?	50	0.5	1
i	P	10	?	?	1	4000	2	2000	20	20

Cont.

Case	Type	I_D	V_{GS}	V_t	V_{OV}	W	L	$\frac{W}{L}$	$\frac{k'W}{L}$	g_m
J	P	10	?	?	4	?	?	125	1.25	5
K	P	0.05	?	?	1	30	3	10	0.1	0.1
L	P	0.1	?	?	5	?	?	0.8	$\frac{8}{1000}$	0.04

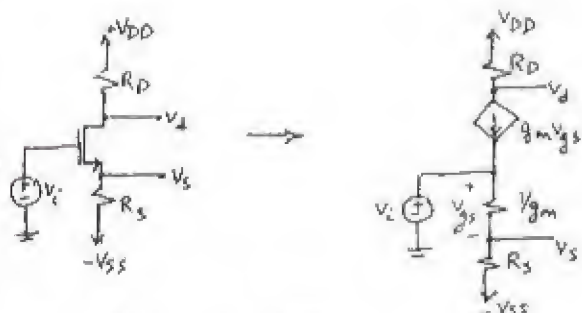
4.73

$$\text{Eq. 4.70: } g_m = \sqrt{2k'_n \frac{W}{L} I_D} \Rightarrow \frac{W}{L} = \frac{g_m^2}{2k'_n I_D}$$

$$\frac{W}{L} = \frac{1}{2 \times 50 \times 10^{-3} \times 0.5} \Rightarrow W = 20 \mu\text{m}$$

$$g_m = \frac{2I_D}{V_{OV}} \Rightarrow V_{OV} = \frac{2 \times 0.5}{1} = 1 \Rightarrow V_{GS} = 1 + V_t = 1.7\text{V}$$

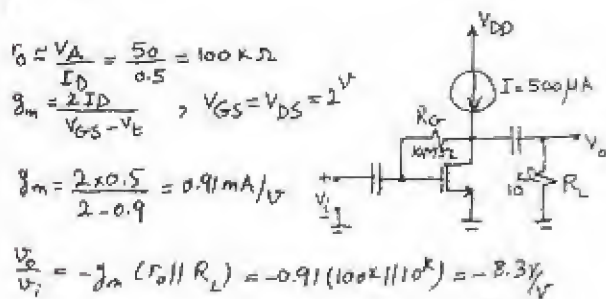
4.74



$$\frac{V_o}{V_i} = \frac{R_D}{R_S + \frac{1}{g_m}} = \frac{R_D g_m}{R_S g_m + 1}$$

$$\frac{V_o}{V_i} = \frac{-g_m V_{GS} R_D}{-g_m R_D} = \frac{1/g_m}{1/g_m + R_S} = \frac{-g_m R_D}{1 + g_m R_S}$$

4.75



$$r_o = \frac{V_A}{I_D} = \frac{50}{0.5} = 100\text{ k}\Omega$$

$$g_m = \frac{2I_D}{V_{GS} - V_t} > V_{GS} = V_{DS} = 2\text{V}$$

$$g_m = \frac{2 \times 0.5}{2 - 0.9} = 0.91\text{ mA/V}$$

$$\frac{V_o}{V_i} = -g_m (r_o \parallel R_L) = -0.91 (100\text{ k} \parallel 10\text{ k}) = -8.3\text{ V/V}$$

For $I = 1\text{ mA}$ or twice the current:

$$\frac{I_{D1}}{I_{D2}} = \frac{(V_{GS1} - V_t)^2}{(V_{GS2} - V_t)^2} \Rightarrow V_{GS2} = V_t + \sqrt{2} (V_{GS1} - V_t)$$

$$V_{GS2} = 0.9 + \sqrt{2} (2 - 0.9) = 2.5\text{V}$$

$$\frac{g_{m1}}{g_{m2}} = \sqrt{\frac{I_{D1}}{I_{D2}}} \Rightarrow g_{m2} = \sqrt{2} g_{m1} = 1.3\text{ mA/V}$$

$$\frac{r_{o1}}{r_{o2}} = \frac{I_{D2}}{I_{D1}} \Rightarrow r_{o2} = \frac{100}{2} = 50\text{ k}\Omega$$

$$A_v = -1.3 \times (50\text{ k} \parallel 10\text{ k}) = -10.8\text{ V/V}$$

4.76

$$\text{NMOS: } g_m = \sqrt{2k'_n \frac{W}{L} I_D} = \sqrt{2 \times 90 \times 10^{-3} \times \frac{20}{2} \times 0.1} = 0.42\text{ mA/V}$$

$$r_o = \frac{|V_A|}{I_D} = \frac{8 \times 2}{0.1} = 160\text{ k}\Omega$$

$$X = \frac{Y}{2\sqrt{2g_m + |V_{SD}|}} = \frac{0.5}{2\sqrt{2 \times 0.42 + 1}} = 0.2$$

$$g_{mb} = X g_m = 0.2 \times 0.42 = 0.084\text{ mA/V}$$

$$g_m = \frac{2I_D}{V_{OV}} \Rightarrow V_{OV} = \frac{2 \times 0.1}{0.42} = 0.48\text{V}$$

$$\text{PMOS: } g_m = \sqrt{2k'_p \frac{W}{L} I_D} = \sqrt{2 \times 30 \times 10^{-3} \times \frac{20}{2} \times 0.1} = 0.24\text{ mA/V}$$

$$r_o = \frac{|V_A|}{I_D} = \frac{12 \times 2}{0.1} = 240\text{ k}\Omega$$

$$X = 0.2 \Rightarrow g_{mb} = 0.2 \times 0.24 = 0.048\text{ mA/V}$$

$$V_{OV} = \frac{2 \times 0.1}{0.24} = 0.83\text{V}$$

4.77

Refer to Fig. P4.77.

$$\text{a) } V_G = 15 \times \frac{5}{10+5} = 5\text{V} \quad V_S = 3 \times I_D \Rightarrow V_{GS} = 5 - 3I_D$$

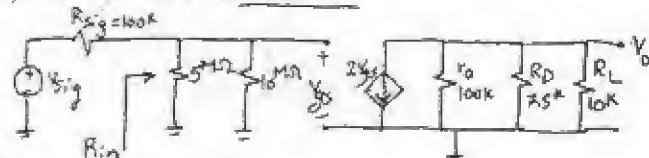
$$I_D = \frac{1}{2} \times k' \frac{W}{L} (V_{GS} - V_t)^2 \Rightarrow I_D = \frac{1}{2} \times 2 \times (5 - 3I_D - 1)^2$$

$$\Rightarrow 16 - 25I_D + 9I_D^2 = 0 \Rightarrow I_D = 1\text{ mA}$$

$$V_{GS} = 2\text{V} \quad V_D = 15 - 7.5 = 7.5\text{V}$$

$$\text{b) } g_m = \frac{2I_D}{V_{OV}} = \frac{2 \times 1}{2 - 1} = 2\text{ mA/V} \quad r_o = \frac{V_A}{I_D} = 100\text{ k}\Omega$$

$$\text{c) } R_{in} = 5\text{ M} \parallel 10\text{ M} = 3.33\text{ M}\Omega$$



$$\text{d) } \frac{V_{GS}}{V_{sig}} = \frac{R_{in}}{R_{sig} + R_{in}} = \frac{3.33}{0.1 + 3.33} = 0.97\text{ V/V}$$

$$\frac{V_o}{V_{GS}} = 2 \times (r_o \parallel R_D \parallel R_L) = 2 \times 4.1\text{ k} = 8.2\text{ V/V} \quad \frac{V_o}{V_{sig}} = 7.95\text{ V/V}$$

4.78

$i_D = \frac{1}{2} K'_n \frac{W}{L} V_{ov}^2$
 The equation for the tangent line passing from point A (V_{ov}, I_D) can be written as:

$$(i_D - I_D) = \left. \frac{\partial i_D}{\partial V_{ov}} \right|_{V_{ov}} (V_{ov} - V_{ov})$$

$$\left. \frac{\partial i_D}{\partial V_{ov}} \right|_{V_{ov}} = K'_n \frac{W}{L} V_{ov}$$

$$\Rightarrow i_D - I_D = K'_n \frac{W}{L} V_{ov} (V_{ov} - V_{ov})$$

$$i_D - \frac{1}{2} K'_n \frac{W}{L} V_{ov}^2 = K'_n \frac{W}{L} V_{ov} (V_{ov} - V_{ov})$$

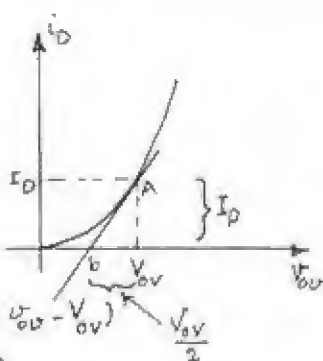
The tangent intersects the V_{ov} axis at $i_D = 0$

$$0 - \frac{1}{2} K'_n \frac{W}{L} V_{ov}^2 = K'_n \frac{W}{L} V_{ov} (V_{ov} - V_{ov})$$

$$-\frac{V_{ov}}{2} = V_{ov} - V_{ov} \Rightarrow V_{ov} = \frac{V_{ov}}{2}$$

The slope of the tangent is g_m and it is

$$\text{equal to: } g_m = \frac{\Delta i_D}{\Delta V_{ov}} = \frac{I_D}{V_{ov} - \frac{V_{ov}}{2}} = \frac{I_D}{\frac{V_{ov}}{2}} = \frac{2I_D}{V_{ov}}$$



$$r_o = \frac{V_A}{I_D} \Rightarrow r_o = 4 \times r_{o1} = 4 \times \frac{75}{0.5} = 600 \text{ k}\Omega$$

$$A_{v0} = -15 \times 2 = -30 \text{ V/V (without } r_o)$$

c) If we take r_o into account:

$$A_{v0} = -g_m (r_o \parallel R_D) = -0.5 (600 \text{ k}\Omega \parallel 60 \text{ k}\Omega) = -27.3 \text{ V/V}$$

$$R_{out} = R_D \parallel r_o = 60 \text{ k}\Omega \parallel 60 \text{ k}\Omega = 30 \text{ k}\Omega$$

$$d) R_{in} = R_G = 4.7 \text{ M}\Omega$$

$$R_o = R_{out} = 30 \text{ k}\Omega$$

$$G_v = \frac{R_{in}}{R_{in} + R_{sig}} A_{v0} \frac{R_L}{R_L + R_o} = \frac{4.7}{4.7 + 0.1} \times \frac{27.3 \times 15}{15 + 30}$$

$$G_v = 5.77 \text{ V/V}$$

e) As we can see by reducing V_{ov} to half of its value or equivalently multiplying drain current by 4, A_{v0} is almost doubled, while R_{out} is multiplied by 4.

As a result G_v , which is proportional to both A_{v0} and $\frac{1}{R_{out}}$ is only slightly reduced. (G_v was -7 V/V before and it is 5.8 V/V now)

4.81

4.79

For this common-source amplifier we have:

$$g_m = \frac{2 \text{ mA}}{V} , r_o = 50 \text{ k}\Omega , R_D = 10 \text{ k}\Omega$$

$$R_G = 10 \text{ M}\Omega , R_{sig} = 0.5 \text{ M}\Omega \text{ and } R_L = 20 \text{ k}\Omega$$

From equation 4.82 we have:

$$G_v = -\frac{R_o}{R_G + R_{sig}} g_m (r_o \parallel R_D \parallel R_L) = -\frac{10 \times 2 (50 \text{ k}\Omega \parallel 10 \text{ k}\Omega \parallel 20 \text{ k}\Omega)}{10 + 0.5}$$

$$G_v = -11.2 \text{ V/V}$$

4.80

$$a) A_{v0} = -2 \frac{(V_{DD} - V_D)}{V_{ov}} = -2 \frac{(10 - 2.5)}{1} = -15 \text{ V/V}$$

b) If V_{ov} is halved ($V_{ov} = 0.5$) then I_D is divided by 4, i.e. $I_D = \frac{0.5}{4} = 0.125 \text{ mA}$

Since V_D is kept unchanged at 2.5 V then:

$$R_D = \frac{10 - 2.5}{0.125} = 60 \text{ k}\Omega , g_m = \frac{2I_D}{V_{ov}} = \frac{0.5 \text{ mA}}{0.5 \text{ V}}$$

For an NMOS common-gate amplifier with $g_m = 5 \text{ mA/V}$, $R_D = 5 \text{ k}\Omega$, $R_L = 2 \text{ k}\Omega$, $R_{sig} = 200 \Omega$ we have:

$$R_{in} = \frac{1}{g_m} = \frac{1}{5} = 0.2 \text{ k}\Omega = 200 \Omega$$

From Eq. 4.96b we know that the overall voltage gain of this amplifier is:

$$G_v = \frac{g_m (R_D \parallel R_L)}{1 + g_m R_{sig}} = \frac{5 (5 \text{ k}\Omega \parallel 2 \text{ k}\Omega)}{1 + 5 \times 0.2} = 3.57 \text{ V/V}$$

If we increase the bias current by a factor of 4, while maintaining the other parameter constant (assuming linear operation), we have:

$$g_m = \sqrt{2 K'_n \frac{W}{L} I_D} \Rightarrow \frac{g_{m2}}{g_{m1}} = \sqrt{\frac{I_{D2}}{I_{D1}}} = \sqrt{4} = 2$$

$$g_{m1} = 2 \times 5 = 10 \text{ mA/V}$$

$$R_{in} = \frac{1}{g_m} = 0.1 \text{ k}\Omega = 100 \Omega$$

$$G_v = g_m \frac{R_D \parallel R_L}{1 + g_m R_{sig}} = 10 \frac{(5 \text{ k}\Omega \parallel 2 \text{ k}\Omega)}{1 + 10 \times 0.2} = 4.76 \text{ V/V}$$

4.82

Refer to Eq. 4.90: $G_v = \frac{R_G}{R_G + R_{S1}} \frac{g_m (R_D \parallel R_L)}{1 + g_m R_S}$

$G_{v1} = -16 \text{ V/V}$ reduced by factor of 4:

$$\frac{G_{v2}}{G_{v1}} = \frac{1}{1 + g_m R_S} \Rightarrow \frac{1}{4} = \frac{1}{1 + 2R_S} \Rightarrow R_S = 1.5 \text{ k}\Omega$$

4.83

Eq. 4.90: $G_v = \frac{R_G}{R_G + R_{S1}} \frac{g_m (R_D \parallel R_L)}{1 + g_m R_S}$

$G_v = -10 \text{ V/V}$ for $R_S = 1 \text{ k}\Omega$ and $G_v = -20 \text{ V/V}$ for $R_S = 0$

$$\frac{G_{v1}}{G_{v2}} = \frac{1 + g_m R_{S2}}{1 + g_m R_{S1}} \Rightarrow \frac{10}{20} = \frac{1 + g_m \times 1}{1 + g_m \times 0} \Rightarrow 1 + g_m = 2$$

$$g_m = 1 \text{ mA/V}$$

In order to have $G_v = -8 \text{ V/V}$:

$$\frac{G_{v1}}{G_{v2}} = \frac{20}{8} = \frac{1 + g_m R_{S2}}{1 + 0} \Rightarrow 1 + R_{S3} = 2.5 \Rightarrow R_{S3} = 1.5 \text{ k}\Omega$$

4.84

$A_{v0} = 0.98 \text{ V/V}$ and $A_v = \frac{0.98}{2} = 0.49 \text{ V/V}$ for $R_L = 500 \Omega$

Eq. 4.102a: $A_v = \frac{R_L}{R_L + \frac{1}{g_m}} \Rightarrow 0.49 = \frac{0.5}{0.5 + \frac{1}{g_m}} \Rightarrow g_m = 1.92 \text{ mA/V}$

Eq. 4.103: $A_{v0} = \frac{r_o}{r_o + \frac{1}{g_m}} \Rightarrow 0.98 = \frac{r_o}{r_o + 0.52} \Rightarrow r_o = 25.5 \text{ k}\Omega$

4.85

We have $g_m = 5 \text{ mA/V}$ and $r_o = 20 \text{ k}\Omega$. From

Eq. 4.103 we know: $A_{v0} = \frac{r_o}{r_o + \frac{1}{g_m}} = \frac{20}{20 + \frac{1}{5}} = 0.99 \text{ V/V}$

$$A_{v0} = 0.99 \text{ V/V}$$

From Eq. 4.105: $R_{out} = \frac{1}{g_m} \parallel r_o = \frac{1}{5} \parallel 20 \text{ k} = 198 \Omega$

$$R_{out} \approx 200 \Omega$$

With $R_L = 1 \text{ k}\Omega$ we have:

$$A_v = \frac{R_L \parallel r_o}{R_L \parallel r_o + \frac{1}{g_m}} = \frac{1 \text{ k} \parallel 20 \text{ k}}{(1 \text{ k} \parallel 20 \text{ k}) + \frac{1}{5}} \Rightarrow A_v = 0.83 \text{ V/V}$$

4.86

$$R_{i2} = \frac{1}{g_{m2}} = 50 \Omega \Rightarrow g_{m2} = \frac{1}{50} = 20 \text{ mA/V}$$

If Q_1 is biased the same as Q_2 , then $g_{m1} = g_{m2}$

$$i_{D1} = g_{m1} V_i = 20 \times 5 \text{ mV} = 100 \mu\text{A} \approx 0.1 \text{ mA}$$

$$V_{D1} = i_{D1} \times 50 \Omega = 0.5 \text{ V}$$

In order to have $V_{D2} = V_{D1} = 1 \text{ V}$:

$$V_{D2} = i_{D2} R_{D2} \Rightarrow 1 = 0.1 \times R_{D2} \Rightarrow R_{D2} = 10 \text{ k}\Omega$$

4.87

a) $i_{D1} = 0.1 = \frac{1}{2} \times 0.8 \times V_{ov}^2 \Rightarrow V_{ov} = 0.5 \text{ V}$

$$\Rightarrow V_{GS} = 0.5 + 1 = 1.5 \text{ V}$$

$$V_G = 0 \Rightarrow V_S = -1.5 \text{ V}$$

$$R_S = \frac{-1.5 - (-5)}{0.1} = 35 \text{ k}\Omega$$

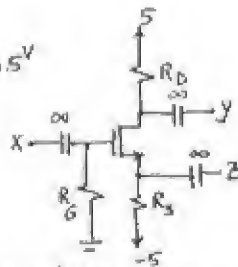
$$V_{DS} = 5 - R_D \times 0.1$$

Largest possible R_D is achieved for V_{DSmin}

$$V_{DS} \geq V_{GS} - V_t \Rightarrow V_{DSmin} = V_{ov} \Rightarrow V_{DS} - 1 = V_{ov}$$

$$\Rightarrow V_{DS} = 1 + 0.5 = 1.5 \text{ V} \Rightarrow R_D = \frac{5 - 1.5}{0.1} = 35 \text{ k}\Omega$$

$$R_G = 10 \text{ M}\Omega$$



b) $g_m = \frac{2I_D}{V_{ov}} = \frac{2 \times 0.1}{0.5} = 0.4 \text{ mA/V}$

$$r_o = \frac{V_A}{I_D} = \frac{40}{0.1} = 400 \text{ k}\Omega$$

c) If Z is grounded then the circuit becomes a common-source configuration. The voltage gain according to Eq. 4.82:

$$G_v = - \frac{R_G}{R_G + R_{S1}} g_m (r_o \parallel R_D \parallel R_L)$$

$$G_v = \frac{10 \text{ M}}{10 \text{ M} + 1 \text{ M}} \times 0.4 \times (400 \text{ k} \parallel 35 \text{ k} \parallel 40 \text{ k}) = 6.5 \text{ V/V}$$

$$G_v = 6.5 \text{ V/V}$$

d) If Y is grounded, then the circuit becomes a source follower configuration.

Eq. 4.103: $A_{v0} = \frac{r_o}{r_o + \frac{1}{g_m}} = \frac{400}{400 + \frac{1}{0.4}} = 0.99 \text{ V/V}$

$$R_{out} = \frac{1}{g_m} \parallel r_o = \frac{1}{0.4} \parallel 400 = 2.48 \text{ k}\Omega$$

$$R_{out} = 2.48 \text{ k}\Omega$$

Cont.

c) If x is grounded, the circuit becomes a common-gate configuration.

$$R_{in} = \frac{1}{g_m} \parallel R_S = 35k \parallel \frac{1}{0.4} = 2.33k\Omega$$

$$\text{Eq. 4.98: } i_c = i_{sig} \frac{R_{sig}}{R_{sig} + R_{in}} \Rightarrow$$

$$i_c = 10\mu A \frac{100k}{100k + 2.33k} = 9.77\mu A$$

$$V_y = R_D \times i_c = 35 \times 9.77\mu A = \underline{0.34V}$$

4.88

a) Fig. P4.85a is a source follower:

$$\text{Eq. 4.103: } A_{v_o} = \frac{r_o}{r_o + \frac{1}{g_m}} ; \quad r_o \gg \frac{1}{g_m} \Rightarrow A_{v_o} \approx \underline{1V/V}$$

$$R_{out} = \frac{1}{g_m} = \frac{1}{5} = \underline{0.2k\Omega}$$

b) Fig. P4.88b is a common-gate configuration:

$$R_{in} = \frac{1}{g_m} \approx \frac{1}{5} = \underline{0.2k\Omega}$$

$$\text{Eq. 4.94: } A_v = g_m (R_D \parallel R_L) = 5 (5k \parallel 2k) = \underline{7.1V/V}$$

c) If we connect both stages together, then:

$$\text{for the first stage: } A_{v_1} = A_{v_o} \frac{R_L}{R_L + R_{out}}$$

where R_L is in fact R_{in} of the second stage.

$$\text{Therefore: } A_{v_1} = 1 \times \frac{0.2k}{0.2 + 0.2} = \underline{0.5V/V}$$

$$\text{For the second stage: } A_{v_2} = \underline{7.1V/V}$$

$$\text{Overall gain } A_v = A_{v_1} A_{v_2} = 7.1 \times 0.5 = \underline{3.55V/V}$$

4.89

4.90

$$C_{ox} = \frac{\epsilon_{ox}}{t_{ox}} = \frac{3.45 \times 10^{-11}}{8 \times 10^{-9}} = 4.3 \times 10^{-3} \text{ F/m}^2 = 4.3 \text{ fF}/\mu\text{m}^2$$

$$k'_n = \mu_n C_{ox} = 450 \times 10^{-4} \times 4.3 \times 10^{-3} = 193.5 \mu\text{A/V}^2$$

$$I_D = 100 \mu\text{A} = \frac{1}{2} \times 193.5 \times \frac{20}{1} V_{ov}^2 \Rightarrow V_{ov} = 0.23 \text{ V}$$

$$V_{DS} = 1.5 \text{ V} > V_{ov} \Rightarrow \text{Saturation}$$

$$g_m = \frac{2I_D}{V_{ov}} = \frac{880 \mu\text{A/V}}{0.23} = 3.826 \text{ mA/V}$$

$$r_o = \frac{1}{\lambda I_D} = \frac{1}{0.05 \times 0.1} = 200 \text{ k}\Omega$$

$$X = \frac{Y}{2\sqrt{2}g_m + Y_{GS}} = \frac{0.5}{2\sqrt{0.65} + 1} = 0.19$$

$$g_{mb} = X g_m = 0.726 \text{ mA/V}$$

$$C_{ov} = W L_{ov} C_{ox} = 20 \times 0.05 \times 4.3 = 4.3 \text{ fF}$$

$$C_{gs} = \frac{2}{3} W L C_{ox} + C_{ov} = \frac{2}{3} \times 20 \times 1 \times 4.3 + 4.3 = 61.6 \text{ fF}$$

$$C_{gd} = C_{ov} = 4.3 \text{ fF}$$

$$C_{sb} = \frac{C_{ov}}{\sqrt{1 + \frac{V_{GS}}{V_0}}} = \frac{4.3}{\sqrt{1 + \frac{1}{0.7}}} = 2.8 \text{ fF}$$

$$C_{db} = \frac{C_{ov}}{\sqrt{1 + \frac{V_{DS}}{V_0}}} = \frac{4.3}{\sqrt{1 + \frac{1.5}{0.7}}} = 2.8 \text{ fF}$$

4.91

$$g_m = \frac{2I_D}{V_{ov}} = \frac{2 \times 0.1}{0.25} = 0.8 \text{ mA/V}$$

$$f_T = \frac{g_m}{2\pi(C_{gs} + C_{gd})} = \frac{0.8 \times 10^{-3}}{2\pi(20 + 5) \times 10^{-15}} = 5.1 \text{ GHz}$$

4.92

$$f_T = \frac{g_m}{2\pi(C_{gs} + C_{gd})}, \quad g_m = \sqrt{2\mu_n C_{ox} \frac{W}{L} I_D}$$

Also $C_{gs} \approx \frac{2}{3} W L C_{ox}$, if $C_{gs} \gg C_{gd}$ then we can ignore C_{gd} . If we replace for g_m and C_{gs} in the f_T formula, we have:

$$f_T = \frac{\sqrt{2\mu_n C_{ox} W/L I_D}}{2\pi \times \frac{2}{3} W L C_{ox}} = \frac{1.5}{\pi L} \sqrt{\frac{\mu_n I_D}{2 C_{ox} W L}}$$

Therefore we can see that the higher the current I_D , then the higher is the f_T . Also the frequency is reverse proportional to the size of the device, i.e. higher frequencies are achievable for smaller devices.

4.93

$$f_T = \frac{g_m}{2\pi(C_{gs} + C_{gd})} \quad (1)$$

For $C_{gs} \gg C_{gd}$ and the overlap capacitance of C_{gs} negligibly small: $C_{gs} \approx \frac{2}{3} W L C_{ox}$

$$\text{Also } g_m = \frac{2I_D}{V_{ov}} = k'_n \frac{W}{L} V_{ov}$$

If we substitute g_m and C_{gs} in (1) from the above formulas: $f_T = k'_n \frac{W}{L} V_{ov} \frac{1}{2\pi \times \frac{2}{3} W L C_{ox}}$

$$\Rightarrow f_T = \frac{3\mu_n V_{ov}}{4\pi L^2}$$

Therefore, for a given device f_T is proportional to V_{ov} . $f_T \propto V_{ov}$

For $L = 1 \mu\text{m}$, $V_{ov} = 0.25$:

$$f_T = \frac{3 \times 450 \times 10^{-4} \times 0.25}{4 \times \pi \times 1 \times 10^{-12}} = 2.7 \text{ GHz}$$

$$\text{For } V_{ov} = 0.5 \text{ V} : \frac{f_{T1}}{f_{T2}} = \frac{V_{ov1}}{V_{ov2}} \Rightarrow \frac{f_{T1}}{f_{T2}} = \frac{2.7 \times 0.5}{0.25} = 5.4 \text{ GHz}$$

4.94

$$A_M = -27 \text{ V/V}, \quad C_{gs} = 0.3 \text{ pF}, \quad C_{gd} = 0.1 \text{ pF}$$

Common-Source configuration.

$$\text{Eq. 4.127: } C_{in} = C_{gs} + C_{gd}(1 + g_m R'_L)$$

Also $A_M = -g_m R'_L$, therefore:

$$C_{in} = 0.3 + 0.1 \times (1 + 27) = 3.1 \text{ pF}$$

Now to find the range of R_{sig} that results in 3-dB frequencies over 10 MHz, we use

$$\text{eq. 4.132: } f_H = \frac{1}{2\pi C_{in} R_{sig}}$$

If we neglect R_G effect then $R'_{sig} \approx R_{sig}$.

$$f_H \geq 10 \text{ MHz} \Rightarrow \frac{1}{2\pi \times 3.1 \times 10^{-12} \times R_{sig}} \geq 10 \text{ MHz}$$

$$\Rightarrow R_{sig} \leq 5.1 \text{ k}\Omega$$

4.95

$$R_{sig} = 100 \text{ k}\Omega, \quad R_{in} = 100 \text{ k}\Omega, \quad C_{gs} = 1 \text{ pF}, \quad C_{gd} = 0.2 \text{ pF}$$

Cont.

$$A_M = -\frac{R_G}{R_G + R_{sig}} g_m (r_o \parallel R_D \parallel R_L) \quad (\text{Eq. 4.119})$$

$$\text{Also } R_{in} = 100 \text{ k}\Omega = R_G$$

$$A_M = \frac{-100}{100+100} 3(50 \text{ k}\Omega \parallel 8 \text{ k}\Omega \parallel 10 \text{ k}\Omega) = -6.1 \text{ V/V}$$

$$f_H = \frac{1}{2\pi C_{in} R'_{sig}} \quad (\text{Eq. 4.132})$$

$$R'_{sig} = R_{sig} \parallel R_G = 100 \parallel 100 = 50 \text{ k}\Omega$$

$$C_{in} = C_{gs} + C_{gd}(1 + g_m R'_L)$$

$$R'_L = r_o \parallel R_D \parallel R_L = 4.1 \text{ k}\Omega$$

$$C_{in} = 1 + 0.2(1 + 3 \times 4.1) = 3.66 \text{ pF}$$

Now we can calculate f_H :

$$f_H = \frac{1}{2\pi \times 3.66 \times 10^{-12} \times 50 \times 10^3} = 870 \text{ kHz}$$

In order to double f_H , we have to either decrease C_{in} (by reducing R_{out}) or reduce R'_{sig} by reducing R_{in} .

If we reduce $R_{out} = R_D \parallel r_o$:

$$\frac{f_{H2}}{f_{H1}} = \frac{C_{in1}}{C_{in2}} \Rightarrow 2 = \frac{3.66 \text{ pF}}{1 + 0.2(1 + 3 \times R'_L)}$$

$$\Rightarrow R'_L = 1.27 \text{ k}\Omega \quad R'_L = R_{out} \parallel R_L = R_{out} \parallel 10 \text{ k}\Omega$$

$$\Rightarrow R_{out} = 1.45 \text{ k}\Omega$$

Therefore in order to double f_H to $870 \times 2 = 1.74 \text{ MHz}$, we have to reduce $R_{out} = r_o \parallel R_D$ to $1.45 \text{ k}\Omega$ or equivalently reducing R_D to $1.5 \text{ k}\Omega$. The new midband gain would be:

$$\frac{A_{M2}}{A_{M1}} = \frac{R'_{L2}}{R'_{L1}} \Rightarrow A_{M2} = 6.1 \times \frac{1.27}{4.1} = 1.9 \text{ V/V}$$

Gain is almost reduced by a factor of 3.

If we reduce $R_{in} = R_G$:

$$\frac{f_{H2}}{f_{H1}} = \frac{R'_{sig1}}{R'_{sig2}} \Rightarrow 2 = \frac{50 \text{ k}\Omega}{R'_{sig2}} \Rightarrow R'_{sig2} = 25 \text{ k}\Omega$$

$$\Rightarrow 25 \text{ k}\Omega = 100 \text{ k}\Omega \parallel R_G \Rightarrow R_G = 33 \text{ k}\Omega = R_{in}$$

Therefore in order to double f_H , R_{in} is reduced by a factor of 3, from $100 \text{ k}\Omega$ to $33 \text{ k}\Omega$.

The new midband gain would be:

$$\frac{A_{M2}}{A_{M1}} = \frac{R_{G2}}{R_{G1}} \frac{R_{L1} + R_{sig1}}{R_{L2} + R_{sig1}} \Rightarrow A_{M2} = 6.1 \times \frac{1}{3} \times \frac{100+100}{33+100}$$

$$A_{M2} = 3.06 \text{ V/V}$$

Gain is almost reduced by a factor of 2.

4.96

$$R_{in} = 2 \text{ M}\Omega, g_m = 4 \text{ mA/V}, r_o = 100 \text{ k}\Omega, R_D = 10 \text{ k}\Omega, C_{gs} = 2 \text{ pF}, C_{gd} = 0.5 \text{ pF}, R_{sig} = 500 \text{ k}\Omega, R_L = 10 \text{ k}\Omega$$

a) using Eq. 4.119 and noting that $R_G = R_{in}$, we have:

$$A_M = -\frac{R_G}{R_G + R_{sig}} g_m (r_o \parallel R_D \parallel R_L) = -\frac{2 \times 4 (100 \text{ k}\Omega \parallel 10 \text{ k}\Omega)}{2+0.5}$$

$$A_M = -15.2 \text{ V/V}$$

b) Eq. 4.132: $f_H = \frac{1}{2\pi C_{in} R'_{sig}}$ where

$$C_{in} = C_{gs} + C_{gd}(1 + g_m (r_o \parallel R_D \parallel R_L)), R'_{sig} = R_{sig} \parallel R_G$$

$$C_{in} = 2 + 0.5(1 + 4 \times (100 \text{ k}\Omega \parallel 10 \text{ k}\Omega)) = 12.02 \text{ pF}$$

$$R'_{sig} = 0.5 \text{ M}\Omega \parallel 2 \text{ M}\Omega = 0.4 \text{ M}\Omega = 400 \text{ k}\Omega$$

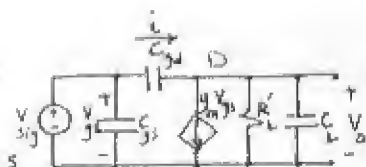
$$f_H = \frac{1}{2\pi \times 12.02 \times 10^{-12} \times 400 \times 10^3} = 33.1 \text{ kHz}$$

4.97

If we write KCL

at node D:

$$i = g_m V_{gs} + \frac{V_D}{R'_L} + V_D C'_L s$$



$$\text{then: } V_{sig} = i \times \frac{1}{C_{gs} s} + V_D$$

$$V_{sig} = (g_m V_{gs} + \frac{V_D}{R'_L} + V_D C'_L s) \frac{1}{C_{gs} s} + V_D, V_{sig} = V_{gs}$$

$$V_{sig} (1 - \frac{g_m}{C_{gs} s}) = V_D (1 + \frac{1}{R'_L C_{gs} s} + \frac{C'_L s}{C_{gs} s})$$

$$\frac{V_D}{V_{sig}} = -\frac{g_m R'_L}{1 - s(C_{gs}/g_m)}$$

$$\frac{V_D}{V_{sig}} = -\frac{g_m R'_L}{1 + s(C_L + C_{gs}) R'_L}$$

$$\text{If } (g_m/C_{gs}) \gg \omega \Rightarrow \frac{V_D}{V_{sig}} = \frac{-g_m R'_L}{1 + s(C_L + C_{gs}) R'_L}$$

$$\text{For } C_{gd} = 0.5 \text{ pF}, C_L = 2 \text{ pF}, g_m = 4 \text{ mA/V}, R'_L = 5 \text{ k}\Omega$$

$$\frac{V_D}{V_{sig}} = \frac{A_M}{1 + s/\omega_H} \Rightarrow \begin{cases} A_M = -g_m R'_L = -4 \times 5 = -20 \text{ V/V} \\ f_H = \frac{1}{2\pi(C_L + C_{gd}) R'_L} \end{cases}$$

$$\Rightarrow f_H = \frac{10^{12}}{2\pi \times (2+0.5) \times 5 \times 10^3}$$

$$f_H = 12.7 \text{ MHz}$$

$$g_m/C_{gd} = \frac{4}{0.5} = 8 \text{ } \omega_{rad/s} \gg \omega_H$$

4.98

Eq. 4.134 $\omega_{p1} = \frac{1}{C_{c1}(R_G + R_{sig})}$
 For $f_p = 10 \text{ Hz}$:

$$2\pi \times 10 = \frac{1}{C_{c1}(1+1) \times 10^6} \Rightarrow C_{c1} = 7.96 \text{ nF}$$

To ensure that f_p is not exceeding 10 Hz ,
 C_{c1} has to be greater than 7.96 nF .
 $C_{c1} = 8 \text{ nF}$. If $C_{c1} = 8 \text{ nF} \Rightarrow f_p = 9.95 \text{ Hz}$

To lower f_p , R_G has to be increased. For the lowest possible f_p , the largest available R_G has to be used, which in this case is $10 \times 1 = 10 \text{ M}\Omega$.

To calculate the new f_p for $R_G = 10 \text{ M}\Omega$:

$$\frac{f_{p2}}{f_{p1}} = \frac{R_G + R_{sig}}{R_{G2} + R_{sig}} \Rightarrow f_{p2} = 9.95 \frac{1+1}{10+1} = 1.81 \text{ Hz}$$

f_p is reduced by a factor of 5.5.

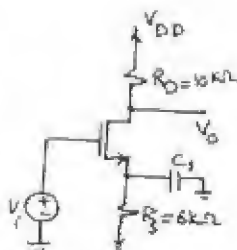
4.99

$I_D = 1 \text{ mA}$, $g_m = 1 \text{ mA/V}$
 Using eq. 4.89 we have:

$$A_M = \frac{-g_m R_D}{1 + g_m R_S} = -\frac{1 \times 10}{1 + 1 \times 6} = -1.43 \text{ V/V}$$

$$f_L = \frac{1}{2\pi \left(\frac{1}{g_m} \parallel R_S \right) C_S} = 10 \text{ Hz}$$

$$C_S = \frac{1}{2\pi \times 10 \left(\frac{1}{1} \parallel 6 \right)} = 18.57 \mu\text{F}$$



4.100

$$f_{c2} = \frac{1}{2\pi C_{c2}(R_L + R_D \parallel r_o)} \ll 10 \text{ Hz}$$

$$\Rightarrow C_{c2} \geq \frac{1}{10 \times 2\pi \times (10^4 + 15^k \parallel 150^k)} \Rightarrow C_{c2} \geq 0.67 \mu\text{F}$$

$$\Rightarrow C_{c2} = 0.7 \mu\text{F} \Rightarrow f_{c2} = 9.62 \text{ Hz}$$

If I_D is doubled with both r_o and R_D halved:

$$f_{c2} = \frac{1}{2\pi \times 0.7 \left(10^4 + \frac{15^k}{2} \parallel \frac{150^k}{2} \right)} = 13.5 \text{ Hz}$$

For higher-power designs, where I_D is increased and consequently r_o and R_D are reduced.

For smallest r_o and R_D where $r_o \parallel R_D \ll R_L$, R_L becomes dominant in determining the corner frequency:

$$f_{c2 \max} = \frac{1}{2\pi C_{c2}(R_L)} = 22.75 \text{ Hz}$$

4.101

Refer to Fig. P4.101: $g_m = 1 \text{ mA/V}$

$$A_M = -\frac{R_G}{R_G + R_{sig}} g_m (R_D \parallel R_L) \text{ where } R_G = 10^4 \parallel 147^k \parallel 8.25^k \Omega$$

$$A_M = -\frac{8.25}{8.25 + 0.1} \times 1 \times (4.7^k \parallel 10^k) = -3.16 \text{ V/V}$$

$$f_{p1} = \frac{1}{2\pi C_{c1}(R_G + R_{sig})} \text{ (Eq. 4.134)}$$

$$f_{p1} = \frac{1}{2\pi \times 0.01 \times 10^{-6} \times (8.25 + 0.1) \times 10^3} = 1.9 \text{ Hz}$$

$$f_{p2} = \frac{1}{2\pi C_S(R_S \parallel \frac{1}{g_m})} = \frac{1}{2\pi \times 10 \times 10^{-6} \times (2^k \parallel \frac{1}{1})} = 23.9 \text{ Hz}$$

$$f_{p3} = \frac{1}{2\pi C_{c2}(R_D + R_L)} = \frac{1}{2\pi \times 0.1 \times 10^{-6} \times (4.7 + 10) \times 10^3} = 108.3 \text{ Hz}$$

$$f_L \approx 108.3 \text{ Hz}$$

4.102

If $g_m = 1 \text{ mA/V}$ and $r_o = 100 \text{ k}\Omega$:

$$A_M = -\frac{R_G}{R_G + R_{sig}} g_m (r_o \parallel R_D \parallel R_L) \text{ where } R_G = 10^4 \parallel 147^k \parallel 8.25^k \Omega$$

$$A_M = -\frac{8.25}{8.25 + 0.1} \times 1 \times (100^k \parallel 4.7^k \parallel 10^k) = -3.06 \text{ V/V}$$

$$f_H = \frac{1}{2\pi C_{in} R_{sig}} \text{ where } R_{sig} = R_{sig} \parallel R_G = 0.1^k \parallel 8.25^k \Omega$$

$$C_{in} = C_{gs} + C_{gd}(1 + g_m(r_o \parallel R_D \parallel R_L))$$

$$C_{in} = 1 + 0.2(1 + 1 \times (100^k \parallel 4.7^k \parallel 10^k)) = 1.82 \text{ pF}$$

$$f_H = \frac{1}{2\pi \times 1.82 \times 10^{-12} \times 0.1 \times 10^3} = 875 \text{ kHz}$$

4.103

$$A_M = -\frac{R_G}{R_G + R_{sig}} g_m (r_o \parallel R_D \parallel R_L) = -\frac{2 \times 3 (20^k \parallel 10^k)}{2 + 0.5}$$

$$A_M = -16 V/V$$

using equations 4.134, 4.136 and 4.138 we have:

$$f_{P1} = \frac{1}{2\pi C_{c1} (R_G + R_{sig})} \Rightarrow 3^{Hz} = \frac{1}{2\pi C_{c1} (2 + 0.5) \times 10^6}$$

$$\Rightarrow C_{c1} = 21.2 \text{ nF}$$

$$f_{P2} = \frac{g_m}{2\pi C_{c2}} \Rightarrow 50^{Hz} = \frac{3 \times 10^{-3}}{2\pi \times C_{c2}} \Rightarrow C_{c2} = 9.6 \mu F$$

$$f_{P3} = \frac{1}{2\pi C_{c3} (R_D + R_L)} \Rightarrow 10^{Hz} = \frac{1}{2\pi C_{c3} (10^k + 20^k)}$$

$$\Rightarrow C_{c3} = 0.5 \mu F$$

$$f_L = 50^{Hz}$$

4.104

Refer to Fig. P4.104.

$$f_{P1} = \frac{1}{2\pi C_{c1} R_{in}} = 1^{Hz} \quad (\text{a decade lower than } 10^{Hz})$$

$$f_{P2} = \frac{1}{2\pi C_{c2} (R_L + R_D \parallel R_o)} = 10^{Hz}$$

$$f_{P1} = 1^{Hz} = \frac{1}{2\pi C_{c1} \times 2.33 \times 10^6} \Rightarrow C_{c1} = 68.3 \text{ nF}$$

$$f_{P2} = 10^{Hz} = \frac{1}{2\pi C_{c2} (10^k + 10^k \parallel 47^k)} \Rightarrow C_{c2} = 873 \text{ nF}$$

4.105

Note that $K_n \frac{W_n}{L_n} = K_p \frac{W_p}{L_p}$ (matched)

a) when V_o is low: (eq. 4.148)

$$r_{DSN} = \frac{1}{K_n \left(\frac{W_n}{L_n}\right) (V_{DD} - V_{tn})} = \frac{1}{120 \times 10^{-6} \times \frac{1.2}{0.8} \times (3 - 0.7)}$$

$$r_{DSN} = 2.4 \text{ k}\Omega$$

when V_o is high (V_{oh}): (eq. 4.141)

$$r_{DSP} = \frac{1}{K_p \left(\frac{W_p}{L_p}\right) (V_{DD} - |V_{tp}|)} = \frac{1}{60 \times 10^{-6} \times \frac{2.4}{0.8} \times (3 - 0.7)}$$

$$r_{DSP} = 2.4 \text{ k}\Omega$$

$$b) I_{max} = K_n' \left(\frac{W_n}{L_n}\right) (V_{DD} - V_{tn}) \times 0.1$$

$$I_{max} = 120 \times 10^{-6} \times \frac{1.2}{0.8} \times (3 - 0.7) \times 0.1 = 41.4 \mu A$$

$$c) \text{ Eq. 4.148: } V_{IH} = \frac{1}{8} (5V_{DD} - 2V_{tn})$$

$$V_{IH} = \frac{1}{8} (5 \times 3 - 2 \times 0.7) = 1.7 \text{ V}$$

$$\text{Eq. 4.149: } V_{IL} = \frac{1}{8} (3V_{DD} + 2V_{tn}) = 1.3 \text{ V}$$

$$V_{MH} = V_{OH} - V_{IH} = 3 - 1.7 = 1.3 \text{ V}$$

$$V_{ML} = V_{IL} - V_{OL} = 1.3 \text{ V} - 0 = 1.3 \text{ V}$$

4.106

From the formula given in Exercise 4.144 we have: $V_{th} = \frac{r(V_{DD} - |V_{tp}|) + V_{tn}}{1 + r}$

$$\text{where } r = \sqrt{\frac{K_p' \left(\frac{W_p}{L_p}\right)}{K_n' \left(\frac{W_n}{L_n}\right)}}$$

We have $V_{tn} = |V_{tp}| = 0.7 \text{ V}$, $V_{DD} = 3 \text{ V}$, $K_n' = 120 \mu A/V^2$, $K_p' = 60 \mu A/V^2$. Thus: For $\left(\frac{W_p}{L_p}\right) = \left(\frac{W_n}{L_n}\right)$ we have:

$$r = \sqrt{\frac{60}{120}} = 0.71$$

$$V_{th} = \frac{0.71(3 - 0.7) + 0.7}{1 + 0.71} = 1.36 \text{ V}$$

For $\left(\frac{W_p}{L_p}\right) = 2 \left(\frac{W_n}{L_n}\right)$ (the matched case)

$$\text{we have: } r = \sqrt{\frac{60}{120} \times 2} = 1$$

$$V_{th} = \frac{1 \times (3 - 0.7) + 0.7}{1 + 1} = 1.5 \text{ V}$$

For $\left(\frac{W_p}{L_p}\right) = 4 \left(\frac{W_n}{L_n}\right)$ we have: $r = \sqrt{\frac{60 \times 4}{120}} = 1.41$

$$V_{th} = \frac{1.41 \times (3 - 0.7) + 0.7}{1 + 1.41} = 1.64 \text{ V}$$

The results are summarized in the following table:

$\left(\frac{W_p}{L_p}\right) = \left(\frac{W_n}{L_n}\right)$	$V_{th} = 1.36 \text{ V}$
$\left(\frac{W_p}{L_p}\right) = 2 \left(\frac{W_n}{L_n}\right)$	$V_{th} = 1.5 \text{ V}$
$\left(\frac{W_p}{L_p}\right) = 4 \left(\frac{W_n}{L_n}\right)$	$V_{th} = 1.64 \text{ V}$

4.107

equal sizes NMOS and PMOS, but $k'_n = 2k'_p$
 $V_t = 0.7V$

for V_{IH} : Q_n in triode and Q_p in saturation

$$k'_n \left(\frac{W}{L}\right)_n \left[(V_I - V_t)V_0 - \frac{1}{2}V_0^2\right] = \frac{1}{2}k'_p \left(\frac{W}{L}\right)_p (V_{DD} - V_I - V_t)^2$$

$$4(V_I - V_t)V_0 - 2V_0^2 = (V_{DD} - V_I - V_t)^2 \quad (1)$$

Differentiating both sides relative to V_I results in:

$$\frac{\partial}{\partial V_I} : 4(V_I - V_t) \frac{\partial V_0}{\partial V_I} + 4V_0 - 4V_0 \frac{\partial V_0}{\partial V_I} = 2(V_{DD} - V_I - V_t)(-1)$$

substitute the values together with $V_I = V_{IH}$,

$$\frac{\partial V_0}{\partial V_I} = -1 :$$

$$4(V_{IH} - 0.7)(-1) + 4V_0 + 4V_0 = 2(V_{DD} - V_{IH} - 0.7)(-1)$$

$$V_{IH} = \frac{8V_0 + 7.4}{6} = 1.33V_0 + 1.23 \quad (2)$$

From (1): $4(V_{IH} - 0.7)V_0 - 2V_0^2 = (3 - V_{IH} - 0.7)^2$

$$(3) \quad 4(V_{IH} - 0.7)V_0 - 2V_0^2 = (2.3 - V_{IH})^2$$

solving (2) and (3): $1.55V_0^2 + 4.97V_0 - 1.14 = 0$

$$\Rightarrow V_0 = 0.21V$$

$$V_{IH} = 1.52V$$

For V_{IL} : Q_n is in saturation and Q_p in triode

$$\frac{1}{2}k'_n \left(\frac{W}{L}\right)_n (V_I - V_t)^2 = k'_p \left(\frac{W}{L}\right)_p \left[(V_{DD} - V_I - V_t)V_0 - \frac{1}{2}(V_{DD} - V_I - V_t)^2\right]$$

$$(V_I - 0.7)^2 = (3 - V_I - 0.7)(3 - V_0) - \frac{1}{2}(3 - V_0)^2 \quad (1)$$

$$(V_I - 0.7)^2 = (2.3 - V_I)(3 - V_0) - \frac{1}{2}(3 - V_0)^2$$

$$\frac{\partial}{\partial V_I} \Rightarrow 2(V_I - 0.7) = (2.3 - V_I)\left(-\frac{\partial V_0}{\partial V_I}\right) - (3 - V_0) + (3 - V_0)\frac{\partial V_0}{\partial V_I}$$

$$V_I = V_{IL} \text{ and } \frac{\partial V_0}{\partial V_I} = -1$$

$$2V_{IL} - 1.4 = 2.3 - V_{IL} - 3 + V_0 + 3 + V_0$$

$$V_{IL} = \frac{2}{3}V_0 - 1.15$$

From (1): $(V_{IL} - 0.7)^2 = (2.3 - V_{IL})(3 - V_0) - \frac{1}{2}(3 - V_0)^2$

$$(0.66V_0 - 1.85)^2 = (3.45 - 0.66V_0)(3 - V_0) - \frac{1}{2}(3 - V_0)^2$$

$$V_0 = 2.96V$$

$$V_{IL} = 0.81V$$

$$NMH = 3 - 1.52 = 1.48V, \quad NML = 0.81 - 0 = 0.81V$$

4.108

matched MOSFETs with $V_t = 1V$, $V_{DD} = 10V$.

$$V_{IL} = \frac{1}{8}(3V_{DD} + 2V_t) \quad \text{Eq. 4.149}$$

$$V_{IL} = \frac{1}{8}(3 \times 10 + 2 \times 1) = 4V$$

$$V_{IH} = \frac{1}{8}(5V_{DD} - 2V_t) \quad \text{Eq. 4.148}$$

$$V_{IH} = \frac{1}{8}(5 \times 10 - 2 \times 1) = 6V$$

$$NMH = V_{OH} - V_{IH} = 10 - 6 = 4V$$

$$NML = V_{OL} - V_{IL} = 4 - 0 = 4V$$

For $V_{DD} = 15V$

$$V_{IL} = \frac{1}{8}(3 \times 15 + 2 \times 1) = 5.875V$$

$$V_{IH} = \frac{1}{8}(5 \times 15 - 2 \times 1) = 9.125V$$

$$NMH = 15 - 9.125 = 5.875V$$

$$NML = 5.875 - 0 = 5.875V$$

4.109

$$V_t = 0.5V$$

$$I_{max} = k'_n \left(\frac{W}{L}\right)_n \left[(V_{DD} - V_{tn}) \times 0.5 - \frac{1}{2} \times 0.5^2\right]$$

$$I_{max} = 20 \times 20 \left[(10 - 0.5) \times 0.5 - 0.125\right]$$

$$I_{max} = 185 \mu A$$

$$V_t = 1.5V \Rightarrow I_{max} = 165 \mu A$$

$$V_t = 2V \Rightarrow I_{max} = 155 \mu A$$

4.110

$$i_{on} = k'_n \left(\frac{W}{L}\right)_n \left[(V_{DD} - V_t)V_0 - \frac{1}{2}V_0^2\right]$$

$$i_{onmax} = k'_n \left(\frac{W}{L}\right)_n \left[(V_{DD} - 0.2V_{DD}) \times 0.1V_{DD} - \frac{1}{2} \times 0.1^2 V_{DD}^2\right]$$

$$i_{onmax} = k'_n \left(\frac{W}{L}\right)_n \times 0.075 V_{DD}^2$$

If $V_{DD} = 3V$, $k'_n = 120 \mu A/V^2$, $L_n = 0.8 \mu m$, $i_{Dmax} = 1 \mu A$

$$i_{Dmax} = 1 = 120 \times 10^{-3} \times \frac{W_n}{0.8} \times 0.075 \times 9$$

$$W_n = 9.9 \mu m$$

4.111

we use the I_{peak} equation given in Table 4.6:

$$I_{\text{peak}} = \frac{1}{2} K'_n \left(\frac{W}{L} \right)_n (V_{DD} - V_{tn})^2$$

$$I_{\text{peak}} = \frac{1}{2} \times 120 \times \frac{1.2}{0.8} \left(\frac{3}{2} - 0.7 \right)^2$$

$$I_{\text{peak}} = 57.6 \mu\text{A}$$

4.112

$$\text{Eq. 4.156: } t_{\text{PHL}} = \frac{2C}{K'_n \left(\frac{W}{L} \right)_n (V_{DD} - V_t) \left[\frac{V_t}{V_{DD} - V_t} + \frac{1}{2} \ln \left(\frac{3V_{DD} - 4V_t}{V_{DD}} \right) \right]}$$

$$\Rightarrow t_{\text{PHL}} = \frac{2 \times 0.05 \times 10^{-12}}{120 \times 10^6 \times \frac{1.2}{0.8} \times (3 - 0.7) \left[\frac{0.7}{3 - 0.7} + \frac{1}{2} \ln \left(\frac{3 \times 3 - 4 \times 0.7}{3} \right) \right]}$$

$$t_{\text{PHL}} = 0.16 \text{ ns}$$

If we use the estimation formula of Eq. 4.157:

$$t_{\text{PHL}} = \frac{1.6C}{K'_n \left(\frac{W}{L} \right)_n V_{DD}} = \frac{1.6 \times 10^{-12} \times 0.05}{120 \times 10^6 \times \frac{1.2}{0.8} \times 3} = 0.15 \text{ ns}$$

The value obtained using the estimation formula is 6% lower. Eq. 4.157 is for $V_t = 0.2V_{DD}$, but in our case $V_t = 0.7 = 0.23V_{DD}$.

4.113

We use the estimation formulas for t_{PHL} and t_{PLH} provided in Table 4.6:

$$t_{\text{PLH}} = \frac{1.6C}{K'_p \left(\frac{W}{L} \right)_p V_{DD}} = \frac{1.6 \times 0.05 \times 10^{-12}}{60 \times 10^6 \times \left(\frac{W}{L} \right)_p \times 3} = \frac{444}{\left(\frac{W}{L} \right)_p} \times 10^{-12} \text{ s}$$

$$\Rightarrow \frac{444}{\left(\frac{W}{L} \right)_p} \leq 60 \Rightarrow \left(\frac{W}{L} \right)_p \geq 7.41 \Rightarrow W_p \geq 5.93 \mu\text{m}$$

$$\left(\frac{W}{L} \right)_p = 2 \left(\frac{W}{L} \right)_n \Rightarrow W_p = 2W_n \Rightarrow W_n \geq 2.97 \mu\text{m}$$

We choose $W_p = 6 \mu\text{m}$ and $W_n = 3 \mu\text{m}$

4.114

At $V_i = V_o = \frac{V_{DD}}{2}$ both Q_n and Q_p are operating in saturation with I_D given by:

$$I_D = \frac{1}{2} K'_n \left(\frac{W}{L} \right)_n \left(\frac{V_{DD}}{2} - V_t \right)^2$$

Thus each device has g_m given by $g_m = \frac{2I_D}{V_{GS} - V_t}$ or $g_m = \frac{2I_D}{V_{DD}/2 - V_t}$ and r_o given by $r_o = \frac{1}{\lambda I_D}$ where we have assumed matched devices: $g_{mn} = g_{mp} = g_m$, $r_{op} = r_{on} = r_o$.

From the small signal equivalent circuit:

$$A_v = \frac{V_o}{V_i} = -g_m (r_{on} \parallel r_{op}) = -g_m r_o$$

Therefore:

$$A_v = -\frac{2 \text{ mA}}{V_{DD} - V_t}$$

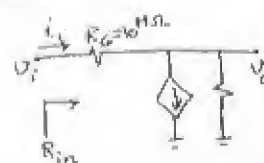
$$b) V_i = V_o = \frac{V_{DD}}{2} = 1.5 \text{ V}$$

$$A_v = -\frac{2 \times 50}{3 - 0.7} = -\frac{100}{2.3} = -43.5 \text{ V/V}$$

$$R_{in} = \frac{V_i}{I_i} = \frac{V_i}{I_D} = \frac{R_G}{1 - A_v}$$

$$R_{in} = \frac{10 \times 10^3}{1 + 43.5} = 229.4 \text{ k}\Omega$$

$$R_{in} \approx 80 \text{ k}\Omega$$



4.115

we have $K'_n \frac{W}{L} = 2 \text{ mA/V}^2$, $V_t = -3 \text{ V}$

$V_{GS} = 0 > V_t \Rightarrow$ device is on

$$V_{GS} - V_t = 3 \text{ V}$$

a) $V_D = 0.1 \text{ V}$, $V_{DS} = 0.1 < V_{GS} - V_t \Rightarrow$ triode region

$$I_D = K'_n \frac{W}{L} \left[(V_{GS} - V_t) V_{DS} - \frac{1}{2} V_{DS}^2 \right]$$

$$I_D = 2 \times \left[3 \times 0.1 - \frac{1}{2} 0.1^2 \right] = 0.59 \text{ mA}$$

b) $V_D = 1 \text{ V} \Rightarrow V_{DS} = 1 \text{ V} < V_{GS} - V_t \Rightarrow$ triode region

$$I_D = 2 \times \left[3 \times 1 - \frac{1}{2} 1^2 \right] = 5 \text{ mA}$$

c) $V_D = 3 \text{ V} \Rightarrow V_{DS} = 3 \text{ V} = V_{GS} - V_t \Rightarrow$ edge of saturation

$$I_D = \frac{1}{2} K'_n \frac{W}{L} (V_{GS} - V_t)^2 = \frac{1}{2} \times 2 \times 3^2 = 9 \text{ mA}$$

d) $V_D = 5 \text{ V}$, $V_{DS} = 5 \text{ V} > V_{GS} - V_t \Rightarrow$ saturation

$$I_D = \frac{1}{2} \times 2 \times 3^2 = 9 \text{ mA}$$



4.116

$$V_{GS} = 0 \quad V_E = -2V \quad V_{GS} - V_E = 2V$$

* $V_{DS} = 1V$: $V_{DS} < V_{GS} - V_E \Rightarrow$ triode

$$i_D = K'_n \frac{W}{L} \left[(V_{GS} - V_E) V_{DS} - \frac{1}{2} V_{DS}^2 \right] = 200 \left[2 \times 1 - \frac{1}{2} \times 1 \right]$$

$$i_D = 300 \mu A$$

If W is doubled, with L the same: $\frac{i_{D2}}{i_{D1}} = \frac{W_2}{W_1} = 2$

$$\Rightarrow i_{D2} = 2 \times 300 = 600 \mu A$$

If W is doubled and L is also doubled, then $\frac{W}{L}$ remains the same and therefore $i_D = 300 \mu A$

* If $V_{DS} = 2V$, then $V_{DS} = V_{GS} - V_E \Rightarrow$ edge of saturation

$$i_D = \frac{1}{2} K'_n \frac{W}{L} (V_{GS} - V_E)^2 (1 + \lambda V_{DS}) = \frac{1}{2} \times 200 \times 2^2 \times (1 + 0.02 \times 2)$$

$$i_D = 416 \mu A$$

If W is doubled and L is the same, then:

$$i_D = 2 \times 416 = 832 \mu A$$

If W is doubled and L is also doubled, then $\frac{W}{L}$

stays the same but $V_A = V'_A L$ is doubled or

equivalently λ is halved, thus:

$$i_D = \frac{1}{2} \times 200 \times 2^2 \times (1 + 0.01 \times 2) = 408 \mu A$$

* If $V_{DS} = 3V$, then $V_{DS} > V_{GS} - V_E \Rightarrow$ saturation

$$i_D = \frac{1}{2} \times 200 \times 2^2 \times (1 + 0.02 \times 3) = 424 \mu A$$

If W is doubled and L is the same: $i_D = 2 \times 424 \Rightarrow$

$$i_D = 848 \mu A$$

If W is doubled and L is also doubled, then $\frac{W}{L}$

stays unchanged, V_A is doubled, λ is halved:

$$\frac{i_{D2}}{i_{D1}} = \frac{(1 + \lambda_2 V_{DS})}{(1 + \lambda_1 V_{DS})} \Rightarrow i_{D2} = 424 \times \frac{(1 + 0.01 \times 3)}{(1 + 0.02 \times 3)} = 412 \mu A$$

* If $V_{DS} = 10V$, then $V_{DS} > V_{GS} - V_E \Rightarrow$ saturation

$$i_D = \frac{1}{2} \times 200 \times 2^2 \times (1 + 0.02 \times 10) = 480 \mu A$$

If W is doubled and L is the same: $i_D = 960 \mu A$

If W is doubled and L is doubled: $i_D = 480 \frac{(1 + 0.01 \times 10)}{1 + 0.02 \times 10}$

$$i_D = 440 \mu A$$

will be operating in the triode region and thus

$$i = K'_n \frac{W}{L} \left[(V - V_E) V - \frac{1}{2} V^2 \right]$$

$$i = \frac{1}{2} K'_n \frac{W}{L} (V^2 - 2V_E V) \quad V \geq V_E$$



For $V < V_E$, the source and drain

exchange roles and the MOSFET operates with

$V_{GS} = 0$ and $V_{DS} = -V \geq -V_E$ which

implies saturation region operation

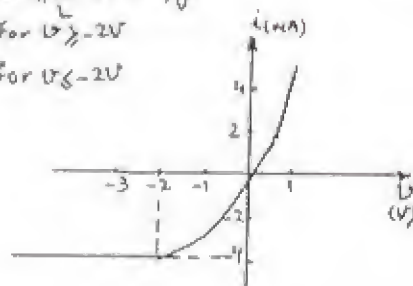
with $i_D = \frac{1}{2} K'_n \frac{W}{L} V_E^2$ (for $V < V_E$)



For $V_E = -2V$ and $K'_n \frac{W}{L} = 2 \text{ mA/V}^2$

$$i = V^2 + 4V \quad \text{for } V \geq -2V$$

$$i = -4 \text{ mA} \quad \text{for } V < -2V$$



4.118

$$K'_n \frac{W}{L} = 4 \text{ mA/V}^2, \quad V_E = -2V$$

Since $V_{DG} \leq |V_E|$, the MOSFET will be operating in the triode region:

$$i_D = K'_n \frac{W}{L} \left[(V_{GS} - V_E) V_{DS} - \frac{1}{2} V_{DS}^2 \right]$$

$$2 = 4 \left[(-V_S + 2)(1 - V_S) - \frac{1}{2} (1 - V_S)^2 \right]$$

$$2 = +4V_S^2 + 8 - 12V_S - 2V_S^2 - 2 + 4V_S$$

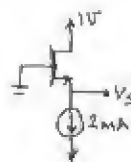
$$2V_S^2 - 8V_S + 4 = 0 \Rightarrow V_S^2 - 4V_S + 2 = 0$$

$$V_S = 3.4V \text{ or } 0.59V$$

The first answer is not physically meaningful,

for it results in $V_{DS} = -3.4 < V_E$ and that implies

cutoff. Therefore: $V_S = 0.59V$



4.119

$$i_D = \frac{1}{2} K'_n \frac{W}{L} (V_{GS} - V_E)^2, \quad \lambda = 0$$

$$\left. \begin{aligned} 1 &= \frac{K'_n \frac{W}{L}}{2} (1 - V_E)^2 \\ 9 &= \frac{K'_n \frac{W}{L}}{2} (1 - V_E)^2 \end{aligned} \right\} \Rightarrow 9 = \frac{(1 - V_E)^2}{(1 - V_E)^2} \Rightarrow \pm 3 = \frac{1 - V_E}{1 + V_E}$$

$$\Rightarrow V_E = -0.5V, -2V$$

Cont.

4.117

$V_{GS} = V_{DS} = V$. For $V \geq V_E$ the device will be conducting and since $V_{DS} = V < V - V_E$, the device

$V_E = -0.5V$ is not acceptable, for it results in $V_{GS} = -1V < V_E$. Therefore $V_E = -2V$.
If we replace this in ①:

$$I = \frac{1}{2} K_n \frac{W}{L} (-1+2)^2 \Rightarrow K_n \frac{W}{L} = 2 \text{ mA/V}^2$$

$$I_{DSS} = \frac{1}{2} K_n \frac{W}{L} V_E^2 = \frac{1}{2} \times 2 \times 2^2 = 4 \text{ mA}$$

4.120

$$I_{DSS} = \frac{1}{2} K_n \frac{W}{L} V_E^2 \Rightarrow 4 = \frac{1}{2} K_n \frac{W}{L} \times 2^2 \Rightarrow K_n \frac{W}{L} = 2 \text{ mA/V}^2$$

Refer to Fig. P4.120

Consider Q_1 : $V_{GS1} = -I_{D1} R_1$

$$I_{D1} = \frac{1}{2} K_n \frac{W}{L} (V_{GS1} - V_E)^2 \Rightarrow 1 = \frac{1}{2} \times 2 \times (V_{GS1} + 2)^2 \Rightarrow$$

$$V_{GS1} = -1V$$

$$R_1 = \frac{1V}{1 \text{ mA}} = 1 \text{ k}\Omega \Rightarrow R_1 = R_2 = 1 \text{ k}\Omega$$

$$V_E = -6V \Rightarrow R_3 = \frac{10-6}{1 \text{ mA}} = 4 \text{ k}\Omega$$

$$V_E = V_A - V_{GS2} - I_{D2} R_2 = 0 - V_{GS1} - I_{D2} R_2 = 0 - (-1) - 1 \times 1$$

$$V_E = 0V \text{ (for } V_A = 0)$$

Now if $V_A = \pm 1V$: $V_E = V_A - V_{GS1} - R_2 I_2 = V_A$

$$\Rightarrow V_E = \pm 1V$$

Since $v_E = v_A$, the source follower has zero offset. Q_2 enters the triode region when:

$$V_E = V_A + |V_E| \Rightarrow V_A = 6 - 2 = 4V$$

Q_1 enters the triode region when $V_E = -10 + 2$
 $V_E = -8V$ which corresponds to $V_A = -8V$

4.121

$$a) v_{s,ig} = v_i$$

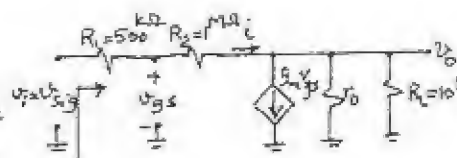
If we write

KCL at the

output node: R_{in}

$$\frac{v_i - v_o}{R_1 + R_2} = g_m v_{gs} + \frac{v_o}{r_o} + \frac{v_o}{R_L} \quad ①$$

$$\text{Also note that } v_{gs} = v_i + R_1 \frac{v_o - v_i}{R_1 + R_2}$$



$$v_{gs} = \frac{R_2}{R_1 + R_2} v_i + \frac{R_1}{R_1 + R_2} v_o$$

By substituting for v_{gs} in ①:

$$\frac{v_i - v_o}{R_1 + R_2} = g_m \frac{R_2}{R_1 + R_2} v_i + \frac{g_m R_1}{R_1 + R_2} v_o + \frac{v_o}{r_o} + \frac{v_o}{R_L}$$

$$v_i \left(\frac{1 - g_m R_2}{R_1 + R_2} \right) = v_o \left(\frac{1 + g_m R_1}{R_1 + R_2} + \frac{1}{r_o} + \frac{1}{R_L} \right)$$

$$\frac{v_o}{v_i} = \frac{1 - g_m R_2}{1 + g_m R_1 + \frac{(R_1 + R_2)}{r_o \parallel R_L}}$$

$$g_m = 1 \text{ mA/V}, r_o = 100 \text{ k}\Omega, R_1 = 0.5 \text{ M}\Omega, R_2 = 1 \text{ M}\Omega, R_L = 10 \text{ k}\Omega$$

$$\frac{v_o}{v_i} = \frac{1 - 1 \times 1000}{1 + 1 \times 500 + \frac{1500}{10 \times 111000}} = -1.5 \text{ V/V}$$

Now we calculate $R_{in} = \frac{v_i}{i_i}$:

$$v_i = (R_1 + R_2) i_i + (i_i - g_m v_{gs}) (r_o \parallel R_L)$$

$$v_{gs} = v_i - R_1 i_i$$

$$v_i = (R_1 + R_2) i_i + (i_i - g_m v_i + g_m R_1 i_i) (r_o \parallel R_L)$$

$$\frac{v_i}{i_i} = R_{in} = \frac{R_1 + R_2 + (1 + g_m R_1) (r_o \parallel R_L)}{1 + g_m (r_o \parallel R_L)}$$

$$R_{in} = \frac{500 + 1000 + (1 + 1 \times 500) \times (10^5 \parallel 10^4)}{1 + 1 \times (10^5 \parallel 10^4)}$$

$$R_{in} = 600 \text{ k}\Omega$$

b) If we write a

KCL for node G:

$$\textcircled{1} \frac{v_{gs} + v_i}{R_1} + g_m v_{gs} + \frac{v_o - v_i}{r_o} + \frac{v_o}{R_L} = 0$$

$$v_i = v_{gs,ig}$$

$$\text{Also: } v_{gs} = v_o \frac{R_1}{R_1 + R_2} - v_i$$

substitute for v_{gs} in ①:

$$\frac{v_o}{R_1 + R_2} - \frac{v_i}{R_1} + \frac{v_i}{R_1} + g_m \frac{R_1}{R_1 + R_2} v_o - g_m v_i + \frac{v_o - v_i}{r_o} + \frac{v_o}{R_L} = 0$$

$$v_o \left(\frac{1 + g_m R_1}{R_1 + R_2} + \frac{1}{r_o} + \frac{1}{R_L} \right) = v_i \left(\frac{1}{R_1} + g_m + \frac{1}{r_o} \right)$$

$$\frac{v_o}{v_i} = \frac{g_m + \frac{1}{r_o}}{\frac{g_m R_1 + 1}{R_1 + R_2} + \frac{1}{r_o} + \frac{1}{R_L}}$$

$$\frac{v_o}{v_i} = \frac{1 + \frac{1}{100}}{\frac{1 \times 500 + 1}{500 + 1000} + \frac{1}{100} + \frac{1}{10}} = 2.27 \text{ V/V}$$

$$\text{Now we find } R_i = \frac{v_i}{i_i}:$$

Cont.

$$i_L = \frac{V_o}{R_1 + R_2} + \frac{V_o}{R_L} \quad (\text{Note that } (R_1 + R_2) \text{ is parallel to } R_L)$$

$$i_L = V_o \left(\frac{1}{R_1 + R_2} + \frac{1}{R_L} \right)$$

$$\frac{i_L}{V_i} = \frac{V_o}{V_i} \left(\frac{1}{R_1 + R_2} + \frac{1}{R_L} \right)$$

$$R_i = \frac{V_i}{i_L} = \frac{1}{\frac{V_o}{V_i} \left(\frac{1}{R_1 + R_2} + \frac{1}{R_L} \right)}$$

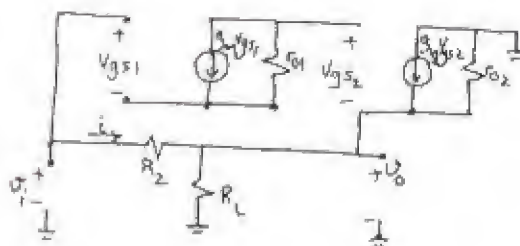
$$R_i = \left(g_m R_L + 1 + \frac{1}{r_o} + \frac{1}{R_L} \right) / \left(g_m + \frac{1}{r_o} \right) \left(\frac{1}{R_1 + R_2} + \frac{1}{R_L} \right)$$

$$R_i = \left(\frac{1 \times 500 + 1}{500 + 1000} + \frac{1}{100} + \frac{1}{10} \right) / \left(1 + \frac{1}{100} \right) \left(\frac{1}{500 + 1000} + \frac{1}{10} \right)$$

$$R_i = 4.37 \text{ k}\Omega$$

$$\Rightarrow 0.8 = R_1 \times 0.01 \Rightarrow R_1 = 80 \text{ k}\Omega$$

$$(R_1 + R_2) \times 0.01 = 2 \text{ V} \Rightarrow R_2 = 120 \text{ k}\Omega$$



$$V_{gs1} = V_i$$

$$V_i = R_2 i + V_o \quad (1)$$

$$V_{gs2} = -g_m V_{gs1} r_o - V_o$$

$$i = \frac{V_o}{R_L} - g_{m2} V_{gs2} + \frac{V_o}{r_{o2}}$$

Substitute i in (1):

$$V_i = R_2 \left(\frac{V_o}{R_L} + g_{m2} V_{gs2} + \frac{V_o}{r_{o2}} \right) + V_o$$

$$\frac{V_o}{V_i} = \frac{1 - g_{m2} R_2 g_{m1} r_{o1}}{\frac{R_2}{R_L} + g_{m2} R_2 + \frac{R_2}{r_{o2}}}$$

We calculate the parameters:

$$g_{m1} = \frac{2 I_D}{V_{ov}} = \frac{2 \times 0.01}{0.2} = 0.1 \text{ mA/V}$$

$$g_{m2} = \frac{2 \times 1}{0.2} = 10 \text{ mA/V}$$

$$r_{o1} = \frac{V_A}{I_D} = \frac{20}{0.01} = 2000 \text{ k}\Omega = 2 \text{ M}\Omega$$

$$r_{o2} = \frac{20}{1} = 20 \text{ k}\Omega$$

$$\frac{V_o}{V_i} = \frac{1 - 10 \times 120 \times 0.1 \times 2000}{\frac{120}{80} + 10 \times 120 + \frac{120}{20}} = -198.8 \text{ V/V}$$

$$\text{We can write: } V_i = V_o + R_2 i_L \Rightarrow 1 = \frac{V_o}{V_i} + R_2 \frac{i_L}{V_i}$$

$$\Rightarrow R_{in} = \frac{V_i}{i_L} = \frac{R_2}{1 - \frac{V_o}{V_i}}$$

$$R_{in} = \frac{120 \text{ k}}{1 + 198.8} = 0.6 \text{ k}\Omega$$

$$\frac{V_o}{V_{sig}} = \frac{R_{in}}{R_1 + R_{in}} \frac{V_o}{V_i} = \frac{0.6 \text{ k}}{80 + 0.6} \times (-198.8) = -1.48 \text{ V/V}$$

This two stage amplifier Consisting of a CS stage followed by a source follower stage with a relatively high gain ($\frac{V_o}{V_i}$) acts similar to an op-amp in an inverting configuration. Also note that $\frac{V_o}{V_{sig}} \approx \frac{R_2}{R_1} \approx 1.5 \text{ V/V}$

Cont.

4.122

For DC-bias analysis purposes, both circuits are basically the same.

$$g_m = \frac{2 I_D}{V_{ov}} \Rightarrow V_{ov} = \frac{2 \times 0.1}{1} = 0.2 \text{ V}$$

$$I_D = \frac{1}{2} K'_n \frac{W}{L} V_{ov}^2 \Rightarrow K'_n \frac{W}{L} = \frac{2 \times 0.1}{0.2^2} = 5 \text{ mA/V}^2$$

$$r_o = \frac{V_A}{I_D} \Rightarrow V_A = 100 \times 0.1 = 10 \text{ V}$$

In order to find the required value for V_{DD} :

$$V_{ov} = V_{GS} - V_t \Rightarrow V_{GS} = 0.2 + 0.6 = 0.8 \text{ V}$$

$$V_{GS} = R_1 I_{R1} \Rightarrow I_{R1} = \frac{0.8}{500 \text{ k}} = 1.6 \mu\text{A}$$

$$V_{DS} = (R_1 + R_2) I_{R1} = (1 + 0.5) \times 1.6 = 2.4 \text{ V}$$

$$V_{DD} = V_{DS} + (I_{R1} + I_D) R_L = 2.4 + (0.0016 + 0.1) \times 10 \text{ k}$$

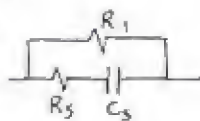
$$V_{DD} = 3.416 \text{ V}$$

4.123

$$V_{R1} = V_{GS} = 0.8 \text{ V} = R_1 I_{R1} \Rightarrow I_{R1} = 0.01 \text{ mA}, I_{D2} = 0.01 \text{ mA}$$

In order to increase the gain magnitude to $\pm 5 V/V$, we need to reduce the effective source resistance R_i . To do so, the following configuration can be used:

To calculate R_S : $R'_i = R_i \parallel R_S$
(midband)



$$\frac{V_o}{V_{sig}} = \frac{R_{in}}{R'_i + R_{in}} \frac{V_o}{V_i}$$

$$-5 = \frac{0.6}{R'_i + 0.6} \times (-198.8) \Rightarrow R'_i = 23.3 k\Omega$$

$$R'_i = 23.3 k = 80 k \parallel R_S \Rightarrow \underline{R_S \approx 33 k\Omega}$$

4.124

$$I_1 = 10 \mu A = I_{D1} = \frac{1}{2} \times 200 \times \left(\frac{W}{L}\right)_1 (0.8 - 0.6)^2$$

$$\Rightarrow \left(\frac{W}{L}\right)_1 = 2.5$$

$$I_{D2} = 1 mA = \frac{1}{2} \times \frac{200}{1000} \times \left(\frac{W}{L}\right)_2 \times (0.8 - 0.6)^2$$

$$\Rightarrow \left(\frac{W}{L}\right)_2 = 250$$

CHAPTER 5 PROBLEMS

5.1

Case	Mode
1	active
2	saturation
3	active
4	saturation
5	inverted active mode
6	active
7	cut-off
8	cut-off

5.2

Using eq. (3.4)

$$I_s = \frac{A_e q D_n n_i^2}{N_A W}$$

$$= \frac{10 \times 10 \times 10^{-4} \times 1.6 \times 10^{-19} \times 21.3 \times 1.5^2 \times 10^{10}}{10^{12} \times 1 \times 10^{-4}}$$

$$= \underline{7.7 \times 10^{-17} \text{ A}}$$

$$\beta = \frac{1}{\frac{D_p N_A W}{D_n N_D L_p} + \frac{1}{2} \frac{W^2}{D_n \tau_b}}$$

$$= \frac{1}{\frac{D_p N_A W}{D_n N_D L_p} + \frac{1}{2} \frac{W^2}{D_n \tau_b}} \quad \text{Eq (5.12)}$$

$$= \frac{1}{\frac{1.7 \times 10^{17} W}{21.3 \times 10^{19} \times 0.6 \times 10^{-14}} + \frac{1}{2} \frac{W^2}{19^2 \times 10^6}}$$

- (a) $W = 10^{-4} \text{ cm}$ $I_s = 7.7 \times 10^{-17} \text{ A}$ $\beta = 368$
 (b) $W = 2 \times 10^{-4} \text{ cm}$ $I_s = 3.8 \times 10^{-17} \text{ A}$ $\beta = 122$
 (c) $W = 6 \times 10^{-4} \text{ cm}$ $I_s = 1.5 \times 10^{-17} \text{ A}$ $\beta = 24.2$

5.3

$$i_c = I_s e^{V_{BE}/V_T}$$

For Device #1

$$0.2 \times 10^{-3} = I_{s1} e^{0.72/0.025}$$

$$I_{s1} = \underline{6.214 \times 10^{-17} \text{ A}}$$

For Device #2

$$12 \times 10^{-3} = I_{s2} e^{0.72/0.025}$$

$$I_{s2} = \underline{3.728 \times 10^{-15} \text{ A}}$$

Since $I_{s2} \gg I_{s1}$, the relative junction areas is:

$$\frac{A_2}{A_1} = \frac{I_{s2}}{I_{s1}} = \frac{i_{c2}}{i_{c1}} = \frac{12}{0.2} = \underline{60}$$

5.4

$$i_c = \beta i_b$$

$$400 = \beta \times 7.5$$

$$\beta = \frac{400}{7.5} = \underline{53.3}$$

$$\alpha = \frac{\beta}{\beta + 1} = \frac{53.3}{54.3} = \underline{0.982}$$

5.5

$$\text{Use } \beta = \alpha / (1 - \alpha)$$

α	β	α	β
0.5	1	0.99	99
0.8	4	0.995	199
0.9	9	0.999	999
0.95	19		

5.6

$$\text{Use } \alpha = \frac{\beta}{\beta+1}$$

β	α	β	α
1	0.5	100	0.9907
2	0.6667	200	0.9950
10	0.9091	1000	0.9990
20	0.9524	2000	0.9995

$$\alpha = \frac{\beta}{\beta+1} = \underline{0.9489}$$

$$I_c = \beta I_B = 18.571 \times 7 \times 10^{-6} = \underline{0.130 \text{ mA}}$$

$$I_c = I_s e^{V_{BE}/V_T}$$

$$I_s = 0.130 \times 10^{-3} e^{-0.58/0.025} = 10.922 \times 10^{-15}$$

$$(d) I_E = I_c + I_B = 10.1 + 0.120 = \underline{10.22 \text{ mA}}$$

$$I_c = \alpha I_E$$

$$\alpha = I_c/I_E = \frac{10.1}{10.22} = \underline{0.9883}$$

$$\beta = I_c/I_B = 10.1/0.120 = \underline{84.167}$$

$$I_c = 10.1 \times 10^{-3} = I_s e^{0.78/0.025}$$

$$I_s = \underline{284.66 \times 10^{-18} \text{ A}}$$

$$(e) I_E = I_c + I_B$$

$$I_c = I_E - I_B = 75 - 1.05 = \underline{73.95 \text{ mA}}$$

$$\alpha = I_c/I_E = 73.95/75 = \underline{0.986}$$

$$\beta = I_c/I_B = 73.95/1.05 = \underline{70.429}$$

$$I_c = 73.95 \times 10^{-3} = I_s e^{0.82/0.025}$$

$$I_s = \underline{4.208 \times 10^{-16} \text{ A}}$$

5.7

$$(a) I_c = \beta I_B$$

$$10^{-3} = \beta \times 30 \times 10^{-6}$$

$$\beta = \underline{20}$$

$$\alpha = \frac{\beta}{\beta+1}$$

$$= \frac{20}{21} = \underline{0.9524}$$

$$I_c = \alpha I_E$$

$$I_E = \frac{I_c}{\alpha} = \frac{10^{-3}}{0.9524}$$

$$= \underline{1.05 \text{ mA}}$$

$$I_c = I_s e^{V_{BE}/V_T}$$

$$I_s = I_c e^{-V_{BE}/V_T}$$

$$= 10^{-3} e^{-0.69/0.025}$$

$$= \underline{1.03 \times 10^{-15} \text{ A}}$$

$$(b) I_c = \alpha I_E$$

$$10^{-3} = \alpha \times 1.07 \times 10^{-3} \Rightarrow \alpha = \underline{0.9346}$$

$$\beta = \frac{\alpha}{1-\alpha} = \underline{14.286}$$

$$I_B = I_c/\beta = \frac{10^{-3}}{14.286} = \underline{69.998 \mu\text{A}}$$

$$I_c = I_s e^{V_{BE}/V_T}$$

$$I_s = 10^{-3} e^{-0.69/0.025} = \underline{1.03 \times 10^{-15}}$$

$$(c) I_c = \alpha I_E = \beta I_B$$

$$\frac{\beta}{\beta+1} I_E = \beta I_B$$

$$I_E = (\beta+1) I_B$$

$$0.137 \times 10^{-3} = (\beta+1) 7 \times 10^{-6} \Rightarrow \beta = \underline{18.571}$$

5.8

$$i_c = I_s e^{V_{BE}}$$

$$10 \times 10^{-3} = I_s e^{0.76/0.025} \Rightarrow I_s = 6.273 \times 10^{-16}$$

$$\text{For } V_{BE} = 0.7 \text{ V} \Rightarrow i_c = 6.273 \times 10^{-16} e^{0.7/0.025}$$

$$= \underline{0.907 \text{ mA}}$$

$$\text{For } i_c = 10 \mu\text{A} \Rightarrow 10 \times 10^{-6} = 6.273 \times 10^{-16} e^{V_{BE}/0.025}$$

$$\therefore V_{BE} = \underline{0.587 \text{ V}}$$

Alternate way - without calculating I_s

For $V_{BE} = 0.7V$

$$\frac{i_c}{10mA} = e^{\frac{0.7 - 0.76}{0.025}}$$

$$\therefore i_c = \underline{0.907mA}$$

For $i_c = 10\mu A$

$$\frac{10 \times 10^{-6}}{10 \times 10^{-3}} = e^{\frac{V_{BE} - 0.76}{0.025}}$$

$$V_{BE} = \underline{0.587V}$$

5.9

$$\beta = \frac{\alpha}{1-\alpha}, \text{ for } \alpha \rightarrow \alpha + \Delta\alpha$$

$$\beta \rightarrow \beta + \Delta\beta$$

$$\beta + \Delta\beta = \frac{\alpha + \Delta\alpha}{1 - \alpha - \Delta\alpha} \text{ solve for } \Delta\beta$$

$$\Delta\beta = \frac{\alpha + \Delta\alpha}{1 - \alpha - \Delta\alpha} - \frac{\alpha}{1 - \alpha}$$

$$= \frac{\alpha}{1 - \alpha} \cdot \frac{1 + \frac{\Delta\alpha}{\alpha}}{1 - \frac{\Delta\alpha}{1 - \alpha}} - \frac{\alpha}{1 - \alpha}$$

$$= \beta \times \frac{\frac{\Delta\alpha}{\alpha} + \frac{\Delta\alpha}{1 - \alpha}}{1 - \frac{\Delta\alpha}{1 - \alpha}}$$

Thus,

$$\frac{\Delta\beta}{\beta} = \frac{\Delta\alpha}{\alpha} \cdot \frac{1 + \frac{\alpha}{1 - \alpha}}{1 - \frac{\Delta\alpha}{1 - \alpha}}$$

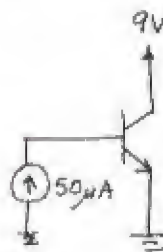
$$= \frac{\Delta\alpha}{\alpha} \cdot \frac{1 - \alpha + \alpha}{1 - \alpha - \Delta\alpha}$$

$$= \frac{\Delta\alpha}{\alpha} \cdot \frac{1}{1 - \alpha - \Delta\alpha}$$

for small $\Delta\alpha$, $\frac{1}{1 - \alpha - \Delta\alpha} \approx \beta$

$$\therefore \frac{\Delta\beta}{\beta} \approx \left(\frac{\Delta\alpha}{\alpha} \right) \beta \quad \text{Q.E.D.}$$

5.10



$$\beta = 60 \text{ to } 300$$

$$I_c = \beta I_B \text{ ranges from}$$

$$= 60 \times 50\mu A \text{ to } 300 \times 50\mu A$$

$$= \underline{3mA \text{ to } 15mA}$$

$$I_E = I_c + I_B \text{ ranges from}$$

$$= \underline{3.05mA \text{ to } 15.05mA}$$

$$\text{Max Power} = 9 \times I_{cmax} = 9 \times 15$$

$$= \underline{135mW}$$

5.11

$$i_c = I_s e^{V_{BE}/V_T}$$

$$10 \times 10^{-3} = I_s e^{0.7/0.025}$$

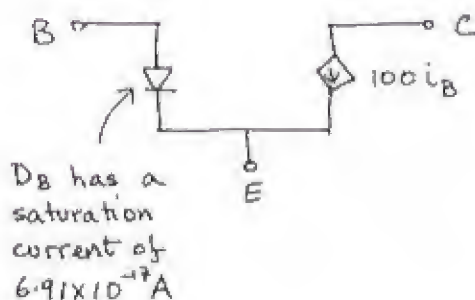
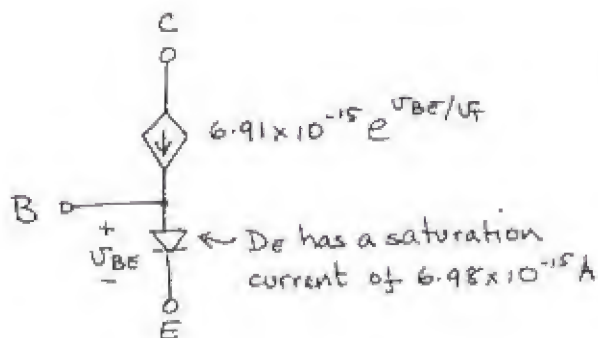
$$\Rightarrow I_s = 6.91 \times 10^{-15} A$$

$$\alpha = \frac{i_c}{i_c + i_B} = \frac{10}{10 + 0.1} = 0.990$$

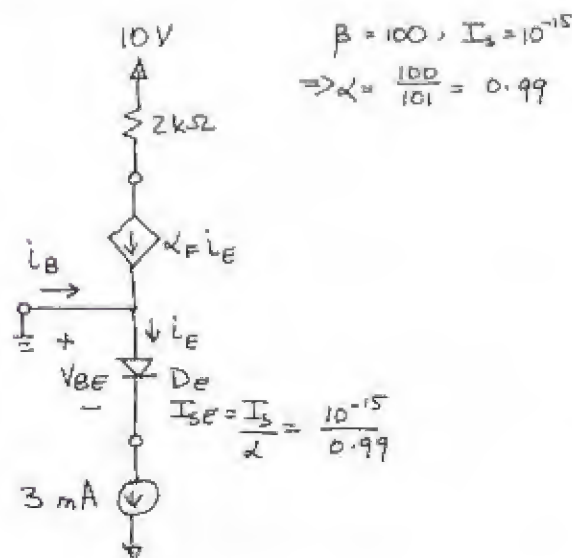
$$\beta = \frac{i_c}{i_B} = \frac{10}{0.1} = 100$$

$$\frac{I_s}{\alpha} = 6.98 \times 10^{-15} A$$

$$\frac{I_s}{\beta} = 6.91 \times 10^{-17} A$$



5.12



$$I_E = I_{SE} e^{V_{BE}/V_T}$$

$$3 \times 10^{-3} = \frac{10^{-15}}{0.99} e^{V_{BE}/0.025}$$

$$V_{BE} = 0.718V$$

$$V_E = 0 - 0.718 = -0.718V$$

$$I_C = \alpha I_E = 0.99 \times 3mA$$

$$V_C = 10 - 2I_C = 10 - 2 \times 0.99 \times 3$$

$$= \underline{4.06V}$$

5.13

$$\beta_F = 100 \quad \alpha_R = 0.01 \quad I_S = 10^{-15} A$$

$$\Rightarrow \alpha_F = 0.99 \quad \beta_R = 0.111$$

(a) Forward Active Mode Operation

$$I_B = 10 \mu A \quad V_{CB} = 1V \quad V_{BE}, I_C, I_E = ?$$

Using the Ebers Moll model we have from eq. (5.28)

$$I_B = \frac{I_S}{\beta_F} \left(e^{V_{BE}/V_T} - 1 \right) + \frac{I_S}{\beta_R} \left(e^{V_{BC}/V_T} - 1 \right)$$

NB. NEGATIVE IN FORWARD ACTIVE MODE

$$10 \times 10^{-6} = \frac{10^{-15}}{100} \left(e^{V_{BE}/0.025} - 1 \right) + \frac{10^{-15}}{0.111} \left(e^{-1/0.025} - 1 \right)$$

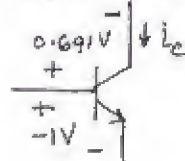
$$= \underline{0.691V}$$

$$I_C = I_S e^{V_{BE}/V_T} = 10^{-15} e^{0.691/0.025}$$

$$= \underline{1mA} \quad \text{NB } I_C = \beta I_B = 100 I_B$$

$$I_E = I_C + I_B = \underline{1.01mA}$$

(b) Reverse Active Mode Operation



Eq (5.28)

$$\begin{aligned}
 i_B &= \frac{I_S}{\beta_F} \left(e^{\frac{V_{BE}}{V_T}} - 1 \right) + \overbrace{\frac{I_S}{\beta_R} \left(e^{\frac{V_{BE}}{V_T}} - 1 \right)}^{\text{this term dominates in reverse active mode}} \\
 &= \frac{10^{-15}}{100} \left(e^{\frac{-1}{0.025}} - 1 \right) + \frac{10^{-15}}{0.111} \left(e^{\frac{0.691}{0.025}} - 1 \right) \\
 &\approx 0 - 10^{-17} + 0.00909 \\
 &= \underline{\underline{9.08 \mu A}}
 \end{aligned}$$

Eq (5.27)

$$\begin{aligned}
 i_C &= I_S \left(e^{\frac{V_{BC}}{V_T}} - 1 \right) - \frac{I_S}{\alpha_R} \left(e^{\frac{V_{BC}}{V_T}} - 1 \right) \\
 &= 10^{-15} \left(e^{\frac{-1}{0.025}} - 1 \right) - \frac{10^{-15}}{0.1} \left(e^{\frac{0.691}{0.025}} - 1 \right) \\
 &\approx 0 - 10^{-15} - 0.01009 \\
 &= \underline{\underline{-10.09 \mu A}}
 \end{aligned}$$

$$i_E = i_C + i_B = \underline{\underline{-1.01 \mu A}}$$

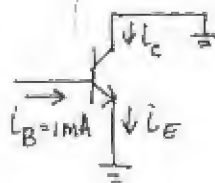
Check with Eq (5.26) - Ebers Moll

$$\begin{aligned}
 i_E &= \underbrace{\frac{I_S}{\alpha_F} \left(e^{\frac{-1}{0.025}} - 1 \right)}_{\approx 0} - I_S \left(e^{\frac{0.691}{0.025}} - 1 \right) \\
 &= \underline{\underline{-1.01 \mu A}}
 \end{aligned}$$

5.14

$$\alpha_F \approx 1$$

$$\therefore \beta_F = \infty$$



$$\alpha_F I_{SE} = \alpha_R I_{SC} = I_S$$

Since $I_S \propto A_{area}$

$$\frac{I_{SC}}{I_{SE}} = \frac{\alpha_F}{\alpha_R} = 10$$

$$\alpha_R = \frac{\alpha_F}{10} = \frac{1}{10}, \quad \beta_R = \frac{\alpha_R}{1 - \alpha_R} = \frac{1}{9}$$

Using Eq (5.26)

$$\begin{aligned}
 i_E &= \frac{I_S}{\alpha_F} \left(e^{\frac{V_{BE}}{V_T}} - 1 \right) - I_S \left(e^{\frac{V_{BC}}{V_T}} - 1 \right) \\
 &= \underline{\underline{0 A}} \quad \text{Since } V_{BE} = V_{BC}
 \end{aligned}$$

Using Eq (5.28)

$$\begin{aligned}
 i_B &= \frac{I_S}{\beta_F} \left(e^{\frac{V_{BE}}{V_T}} - 1 \right) + \frac{I_S}{\beta_R} \left(e^{\frac{V_{BE}}{V_T}} - 1 \right) \\
 &= I_S \left(\underbrace{\frac{1}{\beta_F} + \frac{1}{\beta_R}}_{\approx 0} \right) \left(e^{\frac{V_{BE}}{V_T}} - 1 \right)
 \end{aligned}$$

$$\therefore I_S \left(e^{\frac{V_{BE}}{V_T}} - 1 \right) = \beta_R i_B = \frac{10^{-3}}{9}$$

Using Eq (5.27)

$$\begin{aligned}
 i_C &= I_S \left(e^{\frac{V_{BC}}{V_T}} - 1 \right) - \frac{I_S}{\alpha_F} \left(e^{\frac{V_{BC}}{V_T}} - 1 \right) \\
 &= I_S (1 - 10) \left(e^{\frac{V_{BE}}{V_T}} - 1 \right) \\
 &= -9 \times 10^{-3} / 9 = \underline{\underline{-1 \mu A}}
 \end{aligned}$$

5.15

Using the complete Ebers Moll equations we have:

from Eq (5.26)

$$i_E = \frac{I_S}{\alpha_F} (e^{V_{BE}/V_T} - 1) - I_S (e^{V_{BC}/V_T} - 1)$$

$$\Rightarrow I_S (e^{V_{BE}/V_T} - 1) = \alpha_F (i_E + I_S (e^{V_{BC}/V_T} - 1))$$

substitute this expression in Eq (5.27):

$$i_C = I_S (e^{V_{BE}/V_T} - 1) - \frac{I_S}{\alpha_R} (e^{V_{BC}/V_T} - 1) \quad (A)$$

$$= \alpha_F (i_E + I_S (e^{V_{BC}/V_T} - 1)) - \frac{I_S}{\alpha_R} (e^{V_{BC}/V_T} - 1)$$

$$= \alpha_F i_E + I_S \left(\alpha_F e^{V_{BC}/V_T} - \alpha_F - \frac{1}{\alpha_R} + \frac{1}{\alpha_R} \right)$$

see p 45.9

$i_E = I_E$ since the npn transistor is fed with a constant current

$$= \alpha_F I_E - I_S \left(\frac{1}{\alpha_R} - \alpha_F \right) e^{V_{BC}/V_T} + I_S \left(\frac{1}{\alpha_R} - \alpha_F \right)$$

1

- neglect as $I_S \ll 1$
- this is the same as neglecting terms not involving exponents

Thus,

$$i_C = I_E - I_S \left(\frac{1}{\alpha_R} - \alpha_F \right) e^{V_{BC}/V_T} \quad (B)$$

G.E.D.

(b) $I_S = 10^{-15}$ $\alpha_F \approx 1$ $\alpha_R = 0.1$
 $\beta_F = \infty$

from (B)

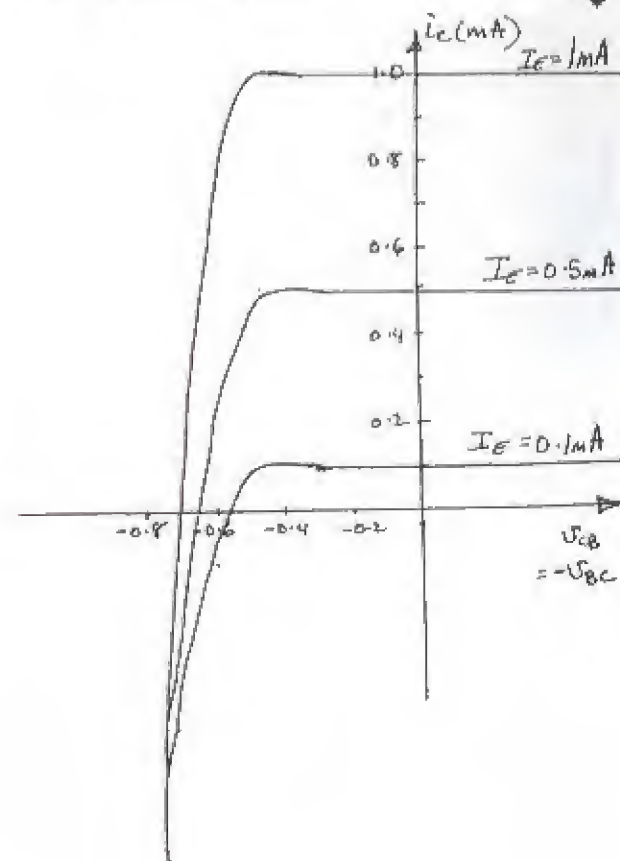
$$i_C = I_E - 9 \times 10^{-15} e^{V_{BC}/0.025} \quad (C)$$

This expression is used to create the

following tables and hence the curves of i_C vs V_{BC} .

V_{BC} (V)	$I_E = 0.1 \text{ mA}$ i_C (mA)	$I_E = 0.5 \text{ mA}$ i_C (mA)	$I_E = 1 \text{ mA}$ i_C (mA)
0.7	-12.92	-12.52	-12.02
0.6	-0.14	0.26	0.762
0.5	+0.1	0.5	1
0.45	+0.1	0.5	1
0.4	0.1	0.5	1
0.35	0.1	0.5	1
0.3	0.1	0.5	1
0	0.1	0.5	1
-1	0.1	0.5	1
-2	0.1	0.5	1

V_{BC} is getting smaller so less current is subtracted from I_E
 $\therefore i_C \rightarrow I_E$



For a particular I_E and i_C , V_{BC} can be calculated using (c)

$$i_C = I_E - 9 \times 10^{-15} e^{V_{BC}/0.025} \quad (1)$$

Having calculated V_{BC} , V_{BE} can be calculated using (A)

$$i_C = 10^{-15} \left(e^{\frac{V_{BE}}{V_T}} - 1 \right) - 10^{-14} \left(e^{\frac{V_{BC}}{V_T}} - 1 \right) \quad (2)$$

Now V_{CE} can be calculated with

$$V_{CE} = -V_{BC} + V_{BE} \quad (3)$$

Thus,

for $I_E = 0.1 \text{ mA}$

i_C (mA)	$V_{BC}(1)$ (V)	$V_{BE}(2)$ (V)	$V_{CE}(3)$ (V)
$0.5 I_E$	0.561	0.644	0.083
0	0.578	0.635	0.067

↓

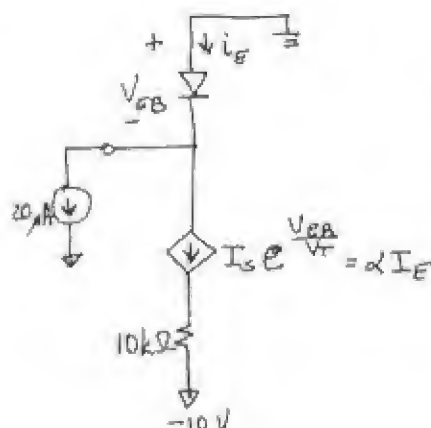
for $I_E = 0.5 \text{ mA}$

i_C (mA)	$V_{BC}(1)$ (V)	$V_{BE}(2)$ (V)	$V_{CE}(3)$ (V)
$0.5 I_E$	0.601	0.674	0.073
0	0.618	0.675	0.057

for $I_E = 1 \text{ mA}$

i_C (mA)	$V_{BC}(1)$ (V)	$V_{BE}(2)$ (V)	$V_{CE}(3)$ (V)
$0.5 I_E = \frac{1}{2}$	0.618	0.691	0.073
0	0.638	0.696	0.058

5.16



$$\beta = 40$$

$$\alpha_F = \frac{40}{41}$$

$$I_S = 10^{-13}$$

$$i_E = \frac{I_S}{\alpha} e^{V_{BE}/V_T} = I_S e^{V_{BE}/V_T} + 0.02 \times 10^{-3}$$

$$I_S e^{V_{BE}/V_T} \left(\frac{1}{\alpha} - 1 \right) = 0.02 \times 10^{-3}$$

$$10^{-13} e^{V_{BE}/0.025} \left(\frac{41}{40} - 1 \right) = 0.02 \times 10^{-3}$$

$$V_{BE} = 0.570 \text{ V} \Rightarrow V_B = \underline{\underline{-0.570 \text{ V}}}$$

$$i_E = \frac{I_S}{\alpha} e^{V_{BE}/V_T} = \frac{10^{-13}}{40} e^{\frac{0.57}{0.025}}$$

$$= \underline{\underline{0.82 \text{ mA}}}$$

$$i_C = \alpha i_E \Rightarrow V_C = -10 + \alpha i_E \times 10$$

$$= -10 + \frac{40}{41} \times 0.82 \times 10$$

$$= \underline{\underline{-2 \text{ V}}}$$

5.17



$$i_C = I_S e^{V_{BE}/V_T}$$

$$V_{BE} \frac{i_C}{1 \text{ A}} = e^{\frac{V_{BE} - 0.8}{0.025}}$$

to calculate V_{BE} for a particular i_C

CONT.

for $I_C = 10 \text{ mA}$ $V_{EB} = 0.685 \text{ V}$
 $I_C = 5 \text{ A}$ $V_{EB} = 0.840 \text{ V}$

5.18



$\beta = 10$

$I_C = \alpha I_E = \frac{10}{11} \times 10 = 9.09 \text{ mA}$

$I_B = I_E - I_C = 0.91 \text{ mA}$

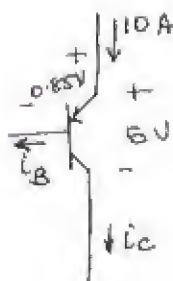
$I_C = I_S e^{V_{EB}/V_T}$
 $9.09 \times 10^{-3} = 10^{-16} e^{V_{EB}/0.025}$

$V_E = V_{EB} = 0.803 \text{ V}$

For $\beta = 1000$

$I_C = \frac{\beta}{\beta+1} I_E = \frac{1000}{1001} \times 10 = 9.99 \text{ mA}$

5.19



for $\beta = 15$

$I_E = (\beta+1) I_B$

$10 = (\beta+1) I_B$

$I_B = \frac{10}{16} = 0.625 \text{ A}$

Calculating I_{S1}

$I_C = \frac{\beta}{\beta+1} I_E = I_{S1} e^{V_{EB}/V_T}$

$\frac{15}{16} \times 10 = I_{S1} e^{0.85/0.025}$

$I_{S1} = 1.608 \times 10^{-14} \text{ A}$

Compare this to

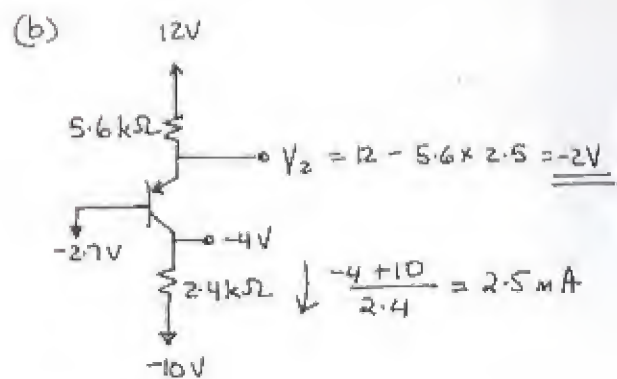
$I_{S2} = I_C e^{-V_{EB}/V_T}$
 $= 10^{-2} e^{-0.7/0.025}$
 $= 6.914 \times 10^{-16}$

$\therefore I_S \propto \text{Area}$

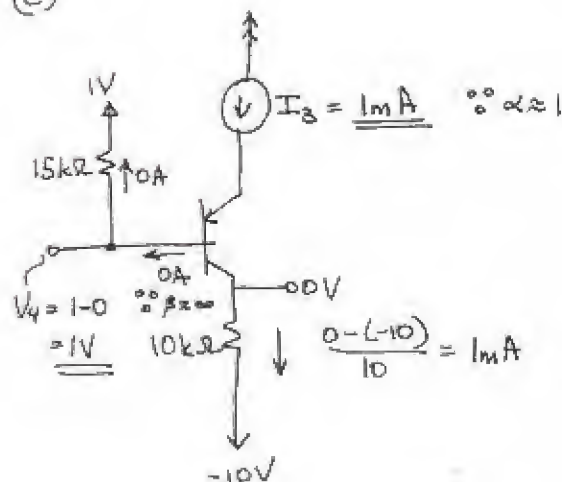
$\frac{\text{Area 1}}{\text{Area 2}} = \frac{I_{S1}}{I_{S2}} = \frac{1.608 \times 10^{-14}}{6.914 \times 10^{-16}}$
 $= 23.3 \text{ times larger}$

5.20

(a) $I_1 = \frac{10.7 - 0.7}{10} = 1 \text{ mA}$

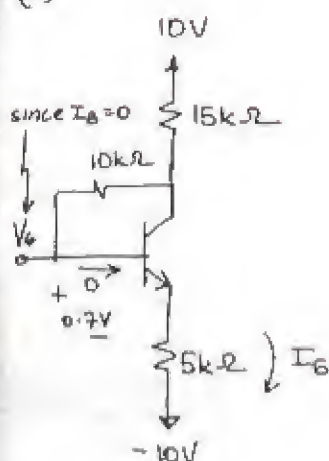


(c)



CONT

(d)



$$I_E = I_C$$

$$\frac{V_B - 0.7 + 10}{5} = \frac{10 - V_B}{15}$$

$$15V_B + 139.5 = 50 - 5V_B$$

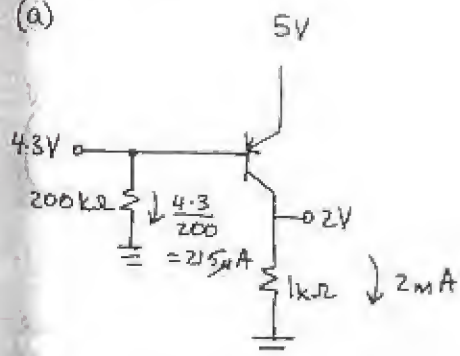
$$V_B = \underline{\underline{-4.475V}}$$

$$I_B = \frac{V_B - 0.7 + 10}{5}$$

$$= \frac{-4.475 - 0.7 + 10}{5} = \underline{\underline{0.965mA}}$$

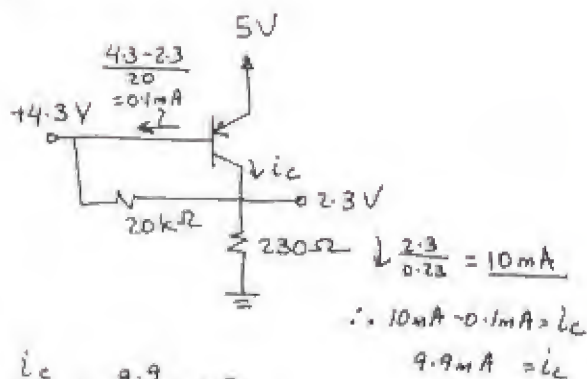
5.21

(a)



$$\frac{I_C}{I_B} = \beta = \frac{2}{0.0215} = \underline{\underline{93.0}}$$

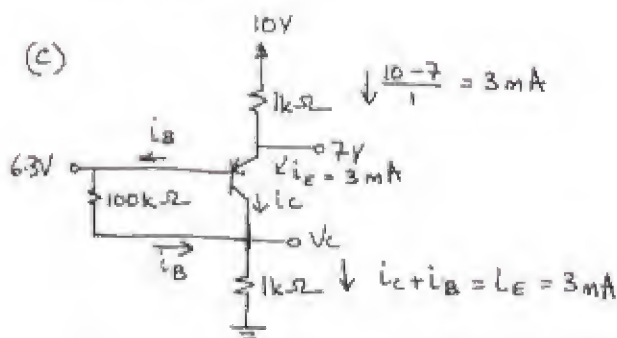
(b)



$$\frac{I_C}{I_B} = \frac{9.9}{0.1} = \beta$$

$$\beta = \underline{\underline{99}}$$

(c)



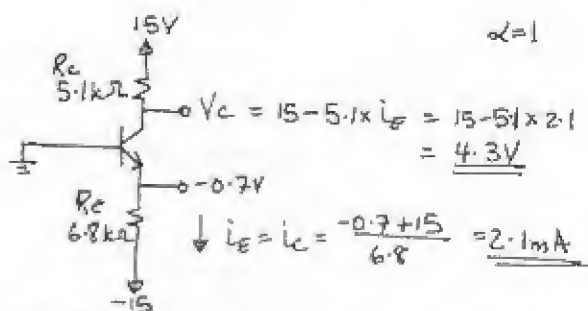
$$V_C = 3 \times 1 = 3V$$

$$I_B = \frac{6.3 - 3}{100} = \frac{3.3}{100}$$

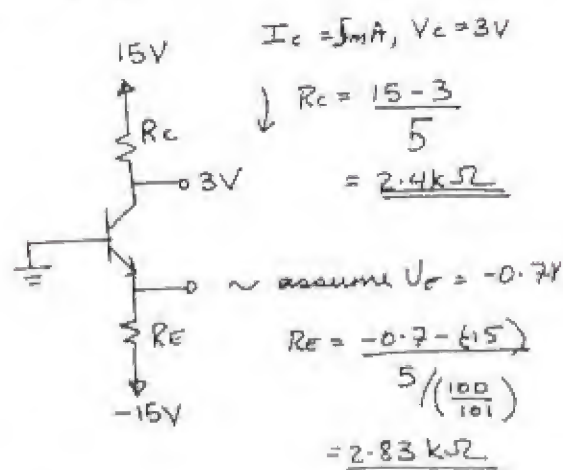
$$\beta + 1 = \frac{I_E}{I_B} = \frac{3 \times 100}{3.3}$$

$$\beta = \frac{300}{3.3} - 1 = \underline{\underline{89.9}}$$

5.22



5.23



(c) $V_B = 3 \text{ V}$

$$V_E = V_B + 0.7 = 3.7 \text{ V}$$

$$I_E = \frac{9 - V_E}{1.1} = \frac{9 - 3.7}{1.1} = 4.82 \text{ mA}$$

$$I_C = \alpha I_E = \frac{30}{31} \times 4.82 = 4.66 \text{ mA}$$

$$V_C = I_C \times 0.56 = 2.62 \text{ V}$$

$$I_B = \frac{I_C}{\beta} = \frac{4.66}{30} = 0.155 \text{ mA}$$

(d) $V_B = 3 \text{ V}$

$$V_E = 3 - 0.7 = 2.3 \text{ V}$$

$$I_E = V_E / 0.47 = 2.3 / 0.47 = 4.89 \text{ mA}$$

$$I_C = \alpha I_E = \frac{30}{31} \times 4.89 = 4.73 \text{ mA}$$

$$V_C = 9 - 1 \times I_C = 9 - 4.73 = 4.22 \text{ V}$$

$$I_B = I_E / \beta = \frac{4.89}{30} = 0.163 \text{ mA}$$

5.24

(a) $V_B = 0 \text{ V}$

$$V_E = V_B - 0.7 = -0.7 \text{ V}$$

$$I_E = \frac{-0.7 + 3}{2.2} = 1.05 \text{ mA}$$

$$I_C = \frac{30}{31} I_E = 1.02 \text{ mA}$$

$$V_C = 3 - 1.02 \times 2.2 = 0.756 \text{ V}$$

$$I_B = \frac{I_C}{\beta} = \frac{1.02}{30} = 0.034 \text{ mA}$$

(b) $V_B = 0 \text{ V}$

$$V_E = V_B + 0.7 = 0.7 \text{ V}$$

$$I_E = \frac{3 - V_E}{1} = \frac{3 - 0.7}{1} = 2.3 \text{ mA}$$

$$I_C = \alpha I_E = \frac{30}{31} \times 2.3 = 2.23 \text{ mA}$$

$$V_C = -3 + 1 \times I_C = -3 + 2.23$$

$$= -0.77 \text{ V}$$

$$I_B = \frac{I_C}{\beta} = \frac{2.23}{30} = 0.0743 \text{ mA}$$

5.25

Instead of V_{BE} being independent of the current level $V_{BE} = 0.7 \text{ V}$ only at $I_C = 1 \text{ mA}$. If I_C is different V_{BE} will change.

(a) $V_E = -V_{BE}$

$$I_C = \alpha I_E = \frac{30}{31} \left(\frac{-V_{BE} + 3}{2.2} \right) = \frac{-30V_{BE} + 90}{31(2.2)}$$

$$\text{so } \frac{I_C}{1 \text{ mA}} = e^{\frac{V_{BE} - 0.7}{0.025}} \quad \text{we have}$$

$$\frac{-30V_{BE} + 90}{31(2.2)} = e^{\frac{V_{BE} - 0.7}{0.025}}$$

CONT.

$$V_{BE} = 0.025 \ln \left(\frac{90 - 30V_{BE}}{31 \times 2.2} \right) + 0.7$$

Iteration #1

$$V_{BE} = 0.7 \rightarrow V_{BE} = 0.70029 \approx 0.7V$$

∴ All the values calculated in 5.24(a) remain the same. This makes sense as I_C in 5.24(a) was 1.02mA which has a rated V_{BE} voltage of 0.7V. Specifically we have:

$$\begin{aligned} V_B &= 0V & I_B &= 0.034mA \\ V_E &= -0.7V & I_E &= 1.05mA \\ V_C &= 0.756V & I_C &= 1.02mA \end{aligned}$$

(b) Continuing to use the iterative process on relative currents

$$\frac{I_C}{1mA} = e^{\frac{V_{BE} - 0.7}{0.025}} \quad \text{we have:}$$

$$\frac{I_C}{1} = \frac{\alpha I_E}{1} = e^{\frac{V_{BE} - 0.7}{0.025}}$$

$$\frac{30}{31} \left(\frac{3 - V_{BE}}{1} \right) = e^{\frac{V_{BE} - 0.7}{0.025}}$$

$$V_{BE} = 0.7 + 0.025 \ln \left(\frac{90 - 30V_{BE}}{31} \right)$$

By Iteration

$$V_{BE} = 0.7V \rightarrow 0.72V \rightarrow 0.72V$$

$$V_E = 0.72V \quad I_E = \frac{3 - 0.72}{1} = 2.28mA$$

$$I_C = \frac{30}{31} I_E = 2.21mA$$

$$V_C = -3 + 2.21 = -0.79V$$

$$V_B = 0 \quad I_B = I_C / \beta = \frac{2.21}{30} = 0.074mA$$

$$(c) I_C = \alpha I_E = e^{\frac{V_{BE} - 0.7}{0.025}}$$

$$\frac{30}{31} \left(\frac{9 - (3 + V_{BE})}{1} \right) = e^{\frac{V_{BE} - 0.7}{0.025}}$$

$$V_{BE} = 0.7 + 0.025 \ln \left[\frac{180 - 30V_{BE}}{31} \right]$$

By Iteration

$$V_{BE} = 0.7 \rightarrow 0.741 \rightarrow 0.741$$

$$\therefore V_E = 3.741V \quad I_E = \frac{9 - 3.741}{1.1} = 4.78mA$$

$$I_C = \frac{30}{31} I_E = 4.63mA \quad V_C = 0.56 I_C = 2.59V$$

$$I_B = \frac{I_C}{30} = 0.154mA \quad V_B = 3V$$

$$(d) I_C = \alpha I_E = e^{\frac{V_{BE} - 0.7}{0.025}}$$

$$\frac{30}{31} \left(\frac{3 - V_{BE}}{0.47} \right) = e^{\frac{V_{BE} - 0.7}{0.025}}$$

$$V_{BE} = 0.7 + \ln \left[\frac{90 - 30V_{BE}}{31 \times 0.47} \right]$$

By Iteration:

$$V_{BE} = 0.7 \rightarrow 0.739 \rightarrow 0.738 \rightarrow 0.738$$

$$\therefore V_E = 3 - 0.738 = 2.26V$$

$$I_E = V_E / 0.47 = 4.81mA$$

CONT.

$$I_c = \frac{30}{31} I_E = \underline{4.65 \text{ mA}} \quad V_c = 9 - I_c \times 1 = \underline{4.35 \text{ V}}$$

$$I_B = \frac{I_c}{30} = \underline{0.155 \text{ mA}} \quad V_B = \underline{3 \text{ V}}$$

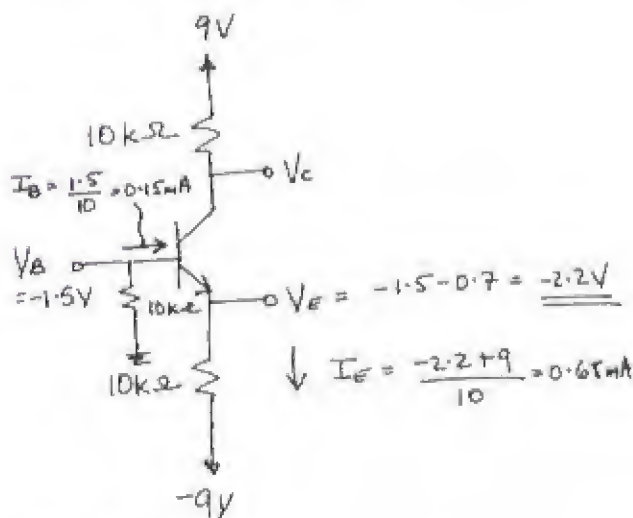
$$I_E = 0.68 \text{ mA}$$

$$I_B = 0 \quad V_B = \underline{0}$$

$$V_c = 9 - 10 I_E = 9 - 6.8 = \underline{2.2 \text{ V}}$$

5.26

FIRST WITH FINITE β



$$\frac{I_E}{I_B} = \beta + 1$$

$$\frac{0.68}{0.15} = \beta + 1 \Rightarrow \beta = \underline{3.63}$$

$$\therefore \alpha = \frac{\beta}{\beta + 1} = \underline{0.779}$$

$$V_c = 9 - 10(\alpha I_E) \\ = 9 - 10(0.779 \times 0.68) \\ = \underline{3.7 \text{ V}}$$

SECOND WITH INFINITE β

$$\beta = \infty \quad V_{BE} = 0.7 \text{ V} \Rightarrow V_E = \underline{-2.2 \text{ V}} \\ \alpha = 1$$

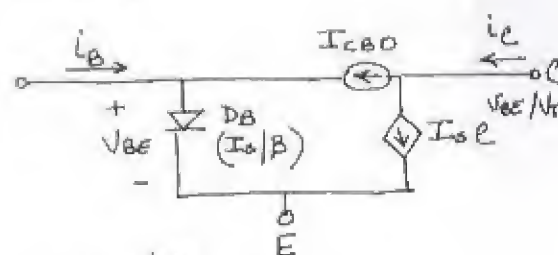
5.27

I_{CBO} doubles for every 10°C rise in temperature.

Thus if $I_{CBO} = 20 \text{ nA}$ at 25°C

$$\text{At } 85^\circ\text{C} \quad I_{CBO} = 2^{\frac{85-25}{10}} \times 20 \\ = \underline{1280 \text{ nA}}$$

5.28



$$I_B = \frac{I_0}{\beta} e^{\frac{V_{BE}}{V_T}} - I_{CBO} \quad (1)$$

$$I_C = I_S e^{\frac{V_{BE}}{V_T}} + I_{CBO} \quad (2)$$

$$I_E = I_S \left(1 + \frac{1}{\beta}\right) e^{\frac{V_{BE}}{V_T}} \quad (3)$$

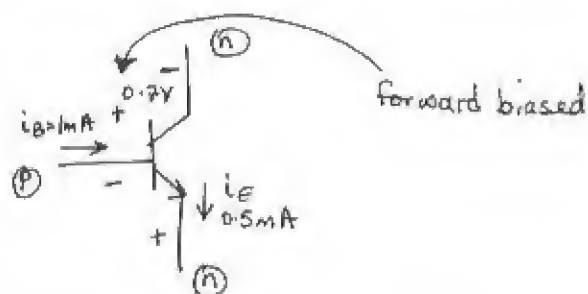
for β open-circuited, $I_B = 0$ and (1) gives:
 $\frac{I_0}{\beta} e^{\frac{V_{BE}}{V_T}} = I_{CBO} \Rightarrow e^{\frac{V_{BE}}{V_T}} = \frac{\beta I_{CBO}}{I_0}$

SUBSTITUTE INTO (2) & (3) \Rightarrow

$$I_C = (\beta + 1) I_{CBO}$$

$$I_E = (\beta + 1) I_{CBO}$$

5.29



Reverse Active Mode - see Table 5.1

Use Ebers Moll Model:

$$i_E = \frac{I_S}{\alpha_F} \left(e^{\frac{V_{BE}}{V_T}} - 1 \right) - I_S \left(e^{\frac{V_{BC}}{V_T}} - 1 \right)$$

NEGLLECT

I_S is small

NEGATIVE AND THUS VERY SMALL

$$i_B = \frac{I_S}{\beta_F} \left(e^{\frac{V_{BE}}{V_T}} - 1 \right) + \frac{I_S}{\beta_R} \left(e^{\frac{V_{BC}}{V_T}} - 1 \right)$$

NEGLLECT THIS TERM

∴ Neglecting the first terms in the expressions for i_E and i_B we have

$$i_E = -I_S \left(e^{\frac{V_{BC}}{V_T}} - 1 \right) = 0.5 \times 10^{-3}$$

$$i_B = \frac{I_S}{\beta_R} \left(e^{\frac{V_{BC}}{V_T}} - 1 \right) = 10^{-3}$$

$$\left| \frac{i_E}{i_B} \right| = \beta_R = \frac{1}{2} \quad \alpha_R = \frac{\beta_R}{\beta_R + 1} = \frac{1}{3}$$

5.30



V_{BE} changes by $-2 \text{ mV}/^\circ\text{C}$

Given $V_{BE} = 0.69 \text{ V}$ at 25°C

Thus,

$$\text{at } 0^\circ\text{C } V_{BE} = 0.69 - 2 \times 10^{-3} (-25) = \underline{\underline{0.74 \text{ V}}}$$

$$\text{At } 100^\circ\text{C } V_{BE} = 0.69 - 2 \times 10^{-3} (75) = \underline{\underline{0.54 \text{ V}}}$$

5.31

Given $i_E = 0.5 \text{ mA}$
 $V_{EB} = 0.692 \text{ V}$ } AT 20°C

(a) The junction temperature rises to 50°C

$$V_{EB} = 0.692 - 2 \times 10^{-3} (50 - 20) = \underline{\underline{0.632 \text{ V}}}$$

(b) The Base-Emitter Voltage is fixed
 $V_{EB} = 0.7 \text{ V}$ at ALL TEMPERATURES

At 20°C ~ $i_E = 0.5 \text{ mA}$ at $V_{EB} = 0.692 \text{ V}$
 Thus for $V_{EB} = 0.7 \text{ V}$ we have

$$\frac{i_E}{0.5 \times 10^{-3}} = e^{\frac{0.7 - 0.692}{0.025}}$$

$$i_E = \underline{\underline{0.689 \text{ mA}}}$$

CONT.

Now if $T = 50^\circ\text{C}$ & $V_{BE} = 0.7\text{V}$

from (a) we see that at 50°C ,

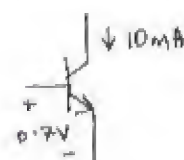
$$I_E = 0.5\text{mA}, \quad V_{BE} = 0.632\text{V}$$

Therefore for $V_{BE} = 0.7\text{V}$

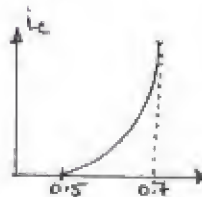
$$\frac{I_E}{0.5 \times 10^{-3}} = e^{\frac{0.7 - 0.632}{0.025}}$$

$$I_E = \underline{\underline{7.59\text{mA}}}$$

5.32



$$\begin{aligned} \frac{I_C}{10\text{mA}} &= e^{\frac{V_{BE} - 0.7}{0.025}} \\ &= e^{\frac{0.5 - 0.7}{0.025}} \end{aligned}$$



$$I_C = \underline{\underline{3.35\mu\text{A}}}$$

Notice the current drops significantly at $V_{BE} = 0.5\text{V}$
See Fig. 5.16

5.33

V_{BE} changes by $-2\text{mV}/^\circ\text{C}$ FOR A PARTICULAR CURRENT. Given that at 25°C $V_{BE} = 0.7\text{V}$ and $I_C = 10\text{mA}$

Thus

$$\begin{aligned} \text{@ } -25^\circ\text{C} \quad V_{BE} &= 0.7 - 2 \times 10^{-3}(-50) \\ &= \underline{\underline{0.8\text{V}}} \quad \text{and } I_C = 10\text{mA} \end{aligned}$$

$$\begin{aligned} \text{@ } 125^\circ\text{C} \quad V_{BE} &= 0.7 - 2 \times 10^{-3}(100) \\ &= \underline{\underline{0.5\text{V}}} \quad \text{and } I_C = 10\text{mA} \end{aligned}$$

5.34

Using the complete Ebers Moll model in eqs. (5.26) and (5.27) and neglecting terms not containing exponentials the I_C dependence on V_{BE} with fixed $I_E = I_E$ can be derived:-

$$\begin{aligned} I_C &= I_S \left(e^{\frac{V_{BE}}{V_T}} - 1 \right) - \frac{I_S}{\alpha_R} \left(e^{\frac{V_{CE}}{V_T}} - 1 \right) \\ &\approx I_S e^{\frac{V_{BE}}{V_T}} - \frac{I_S}{\alpha_R} e^{\frac{V_{CE}}{V_T}} \quad (1) \end{aligned}$$

$$\begin{aligned} I_E &= \frac{I_S}{\alpha_F} \left(e^{\frac{V_{BE}}{V_T}} - 1 \right) - I_S \left(e^{\frac{V_{CE}}{V_T}} - 1 \right) \\ &\approx \frac{I_S}{\alpha_F} e^{\frac{V_{BE}}{V_T}} - I_S e^{\frac{V_{CE}}{V_T}} \end{aligned}$$

Noting the emitter current as being fixed at I_E we get

$$\frac{I_S}{\alpha_F} e^{\frac{V_{BE}}{V_T}} = \alpha_F I_E + \alpha_F I_S e^{\frac{V_{CE}}{V_T}}$$

Substituting This into (1) we get:

$$\begin{aligned} I_C &= \alpha_F I_E + \alpha_F I_S e^{\frac{V_{BE}}{V_T}} - \frac{I_S}{\alpha_R} e^{\frac{V_{CE}}{V_T}} \\ &= \alpha_F I_E + I_S \left(\alpha_F - \frac{1}{\alpha_R} \right) e^{\frac{V_{BE}}{V_T}} \\ &\equiv \text{Eq. (5.35)} \\ &\quad \text{Q.E.D.} \end{aligned}$$

5.35

See details in problem 5.15(b).

-5.36

For the saturated transistor in Fig P.536

$$V_{BC} > 0 \Rightarrow e^{V_{BC}/V_T} \gg 1$$

$$V_{BE} > 0 \Rightarrow e^{V_{BE}/V_T} \gg 1$$

Therefore only exponential terms in the complete Ebers Moll model are kept. Specifically in

Eq(5.27) we have

$$i_c = I_S e^{V_{BE}/V_T} - \frac{I_S}{\alpha_R} e^{V_{BC}/V_T}$$

and in Eq (5.26) we have

$$i_E = \frac{I_S}{\alpha_F} e^{V_{BE}/V_T} - I_S e^{V_{BC}/V_T}$$

$\alpha_F \approx 1$

Noting that $V_{BE} = V_{BC} + V_{CE,sat}$ we get:

$$\frac{i_c}{i_E} = \frac{I_S e^{\frac{V_{BC} + V_{CE,sat}}{V_T}} - \frac{I_S}{\alpha_R} e^{\frac{V_{BC}}{V_T}}}{I_S e^{\frac{V_{BC} + V_{CE,sat}}{V_T}} - I_S e^{\frac{V_{BC}}{V_T}}}$$

$$= \frac{e^{V_{CE,sat}/V_T} - \frac{1}{\alpha_R}}{e^{\frac{V_{CE,sat}}{V_T}} - 1}$$

$$\left(e^{\frac{V_{CE,sat}}{V_T}} - 1 \right) \frac{I_{C,sat}}{I_E} = e^{\frac{V_{CE,sat}}{V_T}} - \frac{1}{\alpha_R}$$

$$e^{\frac{V_{CE,sat}}{V_T}} \left[1 - \frac{I_{C,sat}}{I_E} \right] = \frac{1}{\alpha_R} - \frac{I_{C,sat}}{I_E}$$

$$V_{CE,sat} = V_T \ln \left[\frac{\frac{1}{\alpha_R} - \frac{I_{C,sat}}{I_E}}{1 - \frac{I_{C,sat}}{I_E}} \right] \quad \text{Q.E.D.}$$

Given $\alpha_R = 0.1$ then

$$V_{CE,sat} = 0.026 \ln \left[\frac{10 - \frac{I_{C,sat}}{I_E}}{1 - \frac{I_{C,sat}}{I_E}} \right]$$

$I_{C,sat}/I_E$	$V_{CE,sat} (V)$
0.9	0.113
0.5	0.0736
0.1	0.06
0	0.058

5.37

Eq(5.36):

$$i_c = I_S e^{\frac{V_{BE}}{V_T}} \left(1 + \frac{V_{CE}}{V_A} \right) \leftarrow I_S = 10^{-15} A$$

$V_A = 100V$

$$= 10^{-15} e^{V_{BE}/0.025} \left(1 + \frac{V_{CE}}{100} \right)$$

$V_{BE} = V_{CE}$ (V)	0.65V	0.70V	0.72V	0.73V	0.74V
	i_c (mA)	i_c (mA)	i_c (mA)	i_c (mA)	i_c (mA)
0.2	0.1961	1.4491	3.2251	4.8113	7.1777
0.8	0.1973	1.4578	3.2445	4.8402	7.2207
1.0	0.1977	1.4607	3.2509	4.8498	7.2350
4.0	0.2036	1.5041	3.3475	4.9938	7.4499
10	0.2153	1.5909	3.5406	5.2819	7.8797
12	0.2192	1.6198	3.6409	5.3780	8.0230
15	0.2436	1.6632	3.7015	5.5220	8.2379

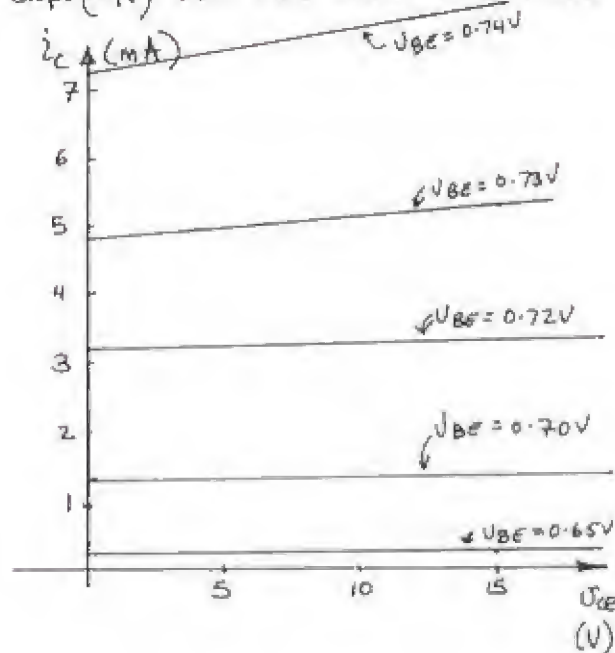
To find the intercept of the straight-line characteristics on the i_c axis, we substitute $V_{CE} = 0$ and evaluate

$$i_c = 10^{-15} e^{V_{BE}/0.025} A \quad \text{for the given}$$

value of V_{BE} . The slope of each straight line is equal to this value divided by 100V (V_A). Thus we obtain

CONT.

V_{BE} (V)	0.65	0.70	0.72	0.73	0.74
Intercept (mA)	0.2	1.45	3.22	4.80	7.16
Slope (mA/V)	0.002	0.015	0.032	0.048	0.072



5.38

$$r_o = \frac{1}{3 \times 10^{-5}} = \underline{\underline{33.3 \text{ k}\Omega}}$$

$$V_A = r_o I_C = 33.3 \times 10^3 \times 3 \times 10^{-3} = \underline{\underline{100 \text{ V}}}$$

$$r_o = \frac{V_A}{I_C} = \frac{100}{30} = \underline{\underline{3.3 \text{ k}\Omega}}$$

5.39

$$r_o = V_A / I_C = 200 / I_C$$

$$@ I_C = 1 \text{ mA} \quad r_o = \underline{\underline{200 \text{ k}\Omega}}$$

$$@ I_C = 100 \mu\text{A} \quad r_o = \frac{200}{0.1} = \underline{\underline{2.0 \text{ M}\Omega}}$$

5.40

$$V_{BE} = 0.72 \text{ V} \quad I_C = 1.8 \text{ mA} \quad V_{CE} = 2 \text{ V}$$

$$I_C = 2.4 \text{ mA} \quad V_{CE} = 14 \text{ V}$$

$$r_o = \frac{\Delta V_{CE}}{\Delta I_C} = \frac{14 - 2}{2.4 - 1.8} = \underline{\underline{20 \text{ k}\Omega}}$$

Near saturation $V_{CE} = 0.3 \text{ V}$

$$\therefore \frac{\Delta V_{CE}}{\Delta I_C} = \frac{0.3 - 2}{I_C - 1.8} = 20$$

$$I_C = \underline{\underline{1.72 \text{ mA}}}$$

calculating V_{CE} for $I_C = 2.0 \text{ mA}$

$$\frac{\Delta V_{CE}}{\Delta I_C} = r_o$$

$$\frac{V_{CE} - 2}{2 - 1.8} = 20 \Rightarrow V_{CE} = \underline{\underline{6 \text{ V}}}$$

Take the ratio of currents to find the Early Voltage (with E_g 5.36)

$$\frac{2.4}{1.8} = e^{\frac{V_{CE} - V_{CE'}}{V_A}} \left(\frac{1 + V_A / V_A}{1 + V_A / V_A} \right)$$

$$= 1$$

$$2.4 + \frac{4.8}{V_A} = 1.8 + \frac{25.2}{V_A}$$

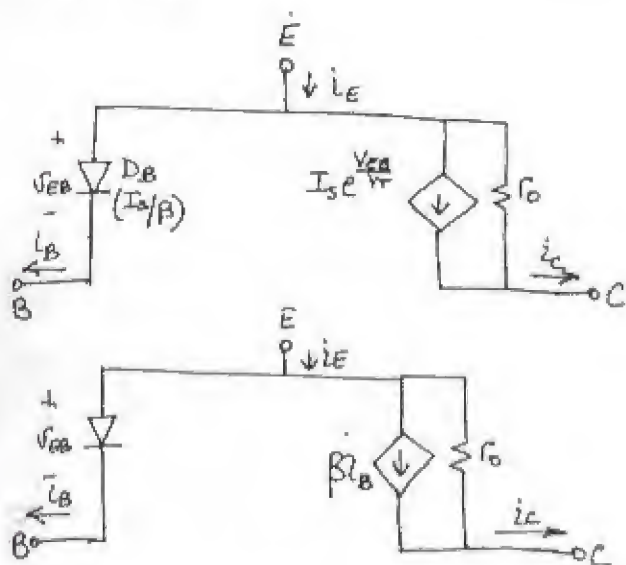
$$V_A = \underline{\underline{34 \text{ V}}}$$

$$r_o = \frac{V_A}{I_C'} \quad \text{where } I_C' \text{ is the current near saturation} \leftrightarrow$$

$$= \frac{34}{1.72} \quad \text{active boundary. As calculated above } I_C' = 1.72$$

$$= \underline{\underline{19.8 \text{ k}\Omega}} \quad \leftarrow \approx \text{to the above calculation of } 20 \text{ k}\Omega$$

5.41



5.42

Large signal or DC β :

$$h_{FE} = \frac{I_C}{I_B} = \frac{1.2 \text{ mA}}{8 \mu\text{A}} = \underline{150}$$

$$\text{Small signal } h_{fe} = \frac{0.1 \text{ mA}}{0.8 \mu\text{A}} = \underline{125}$$

$$r_o = \frac{V_A}{I_C} = \frac{100 \text{ V}}{1.2 \text{ mA}} = 83.3 \text{ k}\Omega$$

$$\Delta I_C = h_{fe} \Delta I_B + \frac{\Delta V_{CE}}{r_o}$$

$$= 125 \times 2 \mu\text{A} + \frac{2}{83.3 \text{ k}\Omega} = 0.274 \text{ mA}$$

$$\therefore I_C = 1.2 \text{ mA} + \Delta I_C = \underline{1.474 \text{ mA}}$$

5.43

	-55°C	25°C	125°C
$I_C = 100 \mu\text{A}$ $\beta \Rightarrow$	100	187	300
$I_C = 10 \text{ mA}$ $\beta \Rightarrow$	78	178	322

For $I_C = 100 \mu\text{A}$

$$\text{Temp. coef below } 25^\circ\text{C} = \frac{187 - 100}{25 - 55} = \underline{1.09/^\circ\text{C}}$$

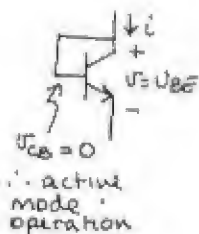
$$\text{Temp. coef above } 25^\circ\text{C} = \frac{300 - 187}{125 - 25} = \underline{1.13/^\circ\text{C}}$$

For $I_C = 10 \text{ mA}$

$$\text{Temp. coef below } 25^\circ\text{C} = \frac{178 - 78}{25 - 55} = \underline{1.25/^\circ\text{C}}$$

$$\text{Temp. coef above } 25^\circ\text{C} = \frac{322 - 178}{125 - 25} = \underline{1.44/^\circ\text{C}}$$

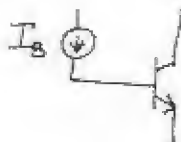
5.44



Use Eq. (5.27) & (5.28)
but neglect $(e^{V_{BE}/V_T} - 1) \approx 0$
terms as $V_{BE} = 0$.

$$\begin{aligned} I &= I_C + I_B \\ &= I_S (e^{V_{BE}/V_T} - 1) + \frac{I_S}{\beta_F} (e^{V_{BE}/V_T} - 1) \\ &= I_S (e^{V_{BE}/V_T} - 1) \left(1 + \frac{1}{\beta_F} \right) \approx \frac{I_S}{\beta_F} e^{V_{BE}/V_T} \\ &= \underline{I_S e^{V_{BE}/V_T}} \quad \text{Q.E.D.} \end{aligned}$$

5.45



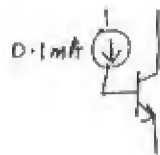
$$V_{CEsat} = V_{CEoff} + I_{Csat} R_{CEsat}$$

O.P. collector is open

$$= V_T \ln \left(\frac{1}{\alpha_F} \right)$$

$$= 0.025 \ln \frac{1}{0.2} = \underline{40.2 \text{ mV}}$$

5.46



$$\beta_{forced} = 20$$

$$\beta_F = 50, \alpha_F = 0.98$$

$$\beta_R = 0.2, \alpha_R = 0.167.$$

Eq (5.48)

$$R_{cesat} = \frac{1}{10\beta_F I_B} = \frac{1}{10 \times 50 \times 0.1} = \underline{\underline{20 \Omega}}$$

Eq (5.49)

$$V_{CEsat} = V_T \ln \left[\frac{1 + \frac{\beta_{forced} + 1}{\beta_R}}{1 - \beta_{forced}/\beta_F} \right]$$

$$= 0.025 \ln \left[\frac{1 + \frac{21}{0.2}}{1 - 20/50} \right] = \underline{\underline{0.187V}}$$

5.47

Using Eq (5.47) which gives the collector current for a transistor in saturation and letting $a = \frac{I_C}{\beta_F I_B}$

we have:

$$I_C = \beta_F I_B \left(\frac{e^{\frac{V_{CE}}{V_T}} - \frac{1}{\alpha_R}}{e^{\frac{V_{CE}}{V_T}} + \frac{\beta_F}{\beta_R}} \right)$$

solve for V_{CE} & take derivative

$$\left. \frac{\partial V_{CE}}{\partial I_C} \right|_{I_B = I_B, I_C = I_{Csat}} = R_{cesat}$$

$$\therefore \frac{I_C}{\beta_F I_B} \left(e^{\frac{V_{CE}}{V_T}} + \frac{\beta_F}{\beta_R} \right) = e^{\frac{V_{CE}}{V_T}} - \frac{1}{\alpha_R}$$

$$e^{\frac{V_{CE}}{V_T}} \left(\frac{I_C}{\beta_F I_B} - 1 \right) = -\frac{\beta_F I_C}{\beta_R \beta_F I_B} - \frac{1}{\alpha_R}$$

$$e^{\frac{V_{CE}}{V_T}} (a - 1) = -\frac{\beta_F}{\beta_R} a - \frac{1}{\alpha_R}$$

$$V_{CE} = V_T \ln \left[\frac{a \frac{\beta_F}{\beta_R} + \frac{1}{\alpha_R}}{1 - a} \right]$$

Now:

$$R_{cesat} = \left. \frac{\partial V_{CE}}{\partial I_C} \right|_{I_C = I_{Csat}}$$

$$= \frac{\partial V_{CE}}{\partial a} \frac{\partial a}{\partial I_C} = \frac{\partial V_{CE}}{\partial a} \times \frac{1}{\beta_F I_B}$$

$$= V_T \left[\frac{1-a}{a \frac{\beta_F}{\beta_R} + \frac{1}{\alpha_R}} \times \left(\frac{\beta_F/\beta_R}{1-a} + \frac{a \beta_F/\beta_R + \frac{1}{\alpha_R}}{(1-a)^2} \right) \right] \frac{1}{\beta_F I_B}$$

$$= \frac{V_T}{\beta_F I_B} \left[\frac{\beta_F/\beta_R}{a \frac{\beta_F}{\beta_R} + \frac{1}{\alpha_R}} + \frac{1}{1-a} \right]$$

$$\approx \frac{1}{a} \quad \because \frac{\beta_F}{\beta_R} a \gg \frac{1}{\alpha_R}$$

$$\approx \frac{V_T}{\beta_F I_B} \left[\frac{1-a+a}{a(1-a)} \right]$$

$$\text{But at } I_C = I_{Csat} \quad a = \frac{I_{Csat}}{\beta_F I_B} = x$$

$$= \frac{V_T}{\beta_F I_B} \times \frac{1}{x(1-x)}$$

Q.E.D.

Using this expression to find R_{cesat} at $\beta_{forced} = \beta_F/2 \Rightarrow x = \frac{\beta_{forced}}{\beta_F} = \frac{1}{2}$

$$R_{cesat} = \frac{V_T}{\beta_F I_B} \times \frac{1}{\frac{1}{2}(1-\frac{1}{2})}$$

$$= \frac{4 \times 0.025}{\beta_F I_B}$$

$$= \frac{1}{10\beta_F I_B} \quad \leftarrow \text{same as eq (5.48)}$$

5.48

$$\beta_F = 70 \rightarrow \alpha_F = 70/71$$

$$\beta_R = 0.7 \rightarrow \alpha_R = \frac{0.7}{8.7}$$

$$I_B = 2 \text{ mA}$$

$$\text{For } i_c = 3 \text{ mA}$$

$$\beta_{\text{forced}} = \frac{3}{2} = 1.5$$

Note the small β_{forced} means we are deeper in saturation. Hence Eq. (5.48) which approximates the slope at $i_c = \frac{\beta_F I_B}{2}$ is not useful here!

Thus we have to use the expression in Problem 5.47

$$\begin{aligned} R_{\text{cesat}} &= \frac{V_T}{\beta_F I_B} \left[\frac{1}{\frac{\beta_{\text{forced}}}{\beta_F} \left(1 - \frac{\beta_{\text{forced}}}{\beta_F} \right)} \right] \\ &= \frac{0.025}{70 \times 2 \times 10^{-3}} \left[\frac{1}{\frac{1.5}{70} \left(1 - \frac{1.5}{70} \right)} \right] \\ &= \underline{\underline{8.516 \, \Omega}} \end{aligned}$$

Using Eq. (5.49) to calculate V_{cesat}

$$\begin{aligned} V_{\text{cesat}} &= V_T \ln \left[\frac{1 + \frac{\beta_{\text{forced}} + 1}{\beta_R}}{1 - \beta_{\text{forced}}/\beta_F} \right] \\ &= 0.025 \ln \left[\frac{1 + \frac{2.5}{0.7}}{1 - 1.5/70} \right] \\ &= 38.5 \text{ mV} \end{aligned}$$

$$\begin{aligned} V_{\text{cesat}} &= V_{\text{ceoff}} + R_{\text{cesat}} I_{\text{csat}} \\ 38.5 &= V_{\text{ceoff}} + 8.516 \times 3 \times 10^{-3} \\ V_{\text{ceoff}} &= \underline{\underline{12.95 \text{ mV}}} \end{aligned}$$

Now for $i_c = 0.3 \text{ mA}$

$$\beta_{\text{forced}} = \frac{0.3}{2} = 0.15$$

$$\begin{aligned} R_{\text{cesat}} &= \frac{V_T}{\beta_F I_B} \left[\frac{1}{\frac{\beta_{\text{forced}}}{\beta_F} \left(1 - \frac{\beta_{\text{forced}}}{\beta_F} \right)} \right] \\ &= \frac{0.025}{70 \times 2 \times 10^{-3}} \left[\frac{1}{\frac{0.15}{70} \left(1 - \frac{0.15}{70} \right)} \right] \\ &= 83.51 \, \Omega \end{aligned}$$

$$\begin{aligned} V_{\text{cesat}} &= 0.025 \ln \left[\frac{1 + \frac{\beta_{\text{forced}} + 1}{\beta_R}}{1 - \beta_{\text{forced}}/\beta_F} \right] \\ &= 0.025 \ln \left[\frac{1 + \frac{1.15}{0.7}}{1 - 0.15/70} \right] \\ &= 24.35 \text{ mV} \end{aligned}$$

Thus V_{ceoff} can be calculated from

$$\begin{aligned} V_{\text{ce,sat}} &= V_{\text{ceoff}} + R_{\text{cesat}} I_{\text{csat}} \\ V_{\text{ceoff}} &= V_{\text{cesat}} - R_{\text{cesat}} I_{\text{csat}} \\ &= 83.51 \times 0.3 \times 10^{-3} \\ &= \underline{\underline{-0.7 \text{ mV}}} \end{aligned}$$

5.49

$$\beta_F = 150 \rightarrow \alpha_F = \frac{150}{151}$$

$$\alpha_F I_{SE} = \alpha_R I_{SC} = I_S$$

$$\frac{A_{CBT}}{A_{EBT}} \propto \frac{I_{SC}}{I_{SE}} = \frac{\alpha_F}{\alpha_R} = 10$$

$$\therefore \alpha_R = \frac{\alpha_F}{10} = 0.0993$$

$$\beta_R = \frac{\alpha_F}{1 - \alpha_F} = 0.110$$

Calculate V_{CEsat} with

$$V_{CEsat} = V_T \ln \left[\frac{1 + \frac{\beta_{forced} + 1}{\beta_R}}{1 - \beta_{forced} \alpha_F} \right]$$

$$= 0.025 \ln \left[\frac{1 + \frac{\beta_{forced} + 1}{0.110}}{1 - \beta_{forced} \alpha_F} \right]$$

$\frac{\beta_{forced}}{\beta_F}$	β_{forced}	V_{CEsat} (V)
0.99	148.5	0.296
0.95	142.5	0.254
0.9	135	0.236
0.5	75	0.180
0.1	15	0.127
0.01	1.5	0.079
0	0	0.068

As β_{forced} is decreased, V_{CEsat} decreases and the BJT is drawn further into saturation.

5.50

$$V_{BE} = 0.72V \text{ at } i_C = 0.6mA$$

(a)

$$\beta_F = 150 \rightarrow \alpha_F = \frac{150}{151} = \underline{\underline{0.993}}$$

$$\frac{A_{CBT}}{A_{EBT}} \propto \frac{I_{SC}}{I_{SE}} = \frac{\alpha_F}{\alpha_R} = 20$$

$$\Rightarrow \alpha_R = \frac{\alpha_F}{20} = \frac{0.993}{20} = \underline{\underline{0.0497}}$$

$$\therefore \beta_R = \underline{\underline{0.0523}}$$

(b) $i_C = 5mA$ - assuming active mode

Using the Ebers Moll model in active mode - Eq (5.32)

$$i_C = I_S e^{V_{BE}/V_T} + I_S \left(\frac{1}{\alpha_R} - 1 \right)$$

$$0.6 \times 10^{-3} = I_S \left(e^{0.72/0.025} + \frac{1}{0.0497} - 1 \right)$$

$$I_S = 1.86 \times 10^{-16}$$

Therefore at $i_C = 5mA$ we have

$$5 \times 10^{-3} = 1.86 \times 10^{-16} \left(e^{V_{BE}/0.025} + \frac{1}{0.0497} - 1 \right)$$

$$V_{BE} = \underline{\underline{0.773V}}$$

Use Eq (5.33) to calculate i_B

$$i_B = \frac{I_S}{\beta_F} e^{V_{BE}/V_T} - I_S \left(\frac{1}{\beta_F} + \frac{1}{\beta_R} \right)$$

$$= \frac{1.86 \times 10^{-16}}{150} e^{\frac{0.773}{0.025}} - 1.86 \times 10^{-16} \left(\frac{1}{150} + \frac{1}{0.0523} \right)$$

$$= \underline{\underline{33.2 \mu A}}$$

CONT.

This value for i_B makes sense as $\frac{i_C}{\beta_F} = \frac{5}{150} = 33.3 \mu A$.

It is a little less due to the reverse leakage currents.

(c) The base current is doubled

$$\left. \begin{array}{l} I_B = 66.4 \mu A \\ I_C = 5 mA \end{array} \right\} \beta_{forced} = \frac{i_C}{i_B} = \frac{I_{Csat}}{I_B} = \frac{5}{0.0664} = 75.3$$

Note β_{forced} is not small so we are not deep in saturation. Hence we can use Eq (5.48) to calculate R_{Csat} :

$$R_{Csat} = \frac{1}{10 \beta_F I_B} = \frac{1}{10 \times 150 \times 66.4 \mu A} = 10.04 \Omega$$

checking this result with the expression from Prob. 5.47 we get the same result:

$$\begin{aligned} R_{Csat} &= \frac{V_T}{\beta_F I_B} \left(\frac{1}{\frac{\beta_{forced}}{\beta_F} \left(1 - \frac{\beta_{forced}}{\beta_F} \right)} \right) \\ &= \frac{0.025}{150 \times 66.4 \times 10^{-6}} \left(\frac{1}{\frac{75.3}{150} \left(1 - \frac{75.3}{150} \right)} \right) \\ &= 10.04 \Omega \end{aligned}$$

From Eq (5.49)

$$|V_{Cesat}| = V_T \ln \left[\frac{1 + \frac{\beta_{forced} + 1}{\beta_F}}{1 - \beta_{forced}/\beta_F} \right]$$

$$\begin{aligned} |V_{Cesat}| &= 0.025 \ln \left[\frac{1 + 76.3/0.0623}{1 - 75.3/150} \right] \\ &= 0.1996 V \end{aligned}$$

Use the complete Ebers Moll equations to calculate V_{BE} and V_{BC} .

$$\begin{aligned} \text{Note that } V_{CE} &= V_{CB} + V_{BE} \\ &= -V_{BC} + V_{BE} \end{aligned}$$

$$\therefore V_{BE} = V_{Cesat} + V_{BC}$$

Eq (5.27):

$$i_C = I_S \left(e^{\frac{V_{BE}}{V_T}} - 1 \right) - I_S / \alpha_R \left(e^{\frac{V_{BC}}{V_T}} - 1 \right)$$

$$\frac{i_C}{I_S} = e^{\frac{V_{Cesat} + V_{BC}}{V_T}} - 1 - \frac{V_{BC}/V_T}{\alpha_R} + \frac{1}{\alpha_R}$$

$$\frac{5 \times 10^{-3}}{1.86 \times 10^{-6}} = e^{\frac{0.1996}{0.025}} e^{\frac{V_{BC}}{V_T}} - 1 - \frac{V_{BC}/V_T}{\alpha_R} + \frac{1}{\alpha_R}$$

$$\begin{aligned} V_{BC} &= 0.025 \ln \left[\frac{\frac{5 \times 10^{-3}}{1.86 \times 10^{-6}} + 1 - \frac{1}{0.0497}}{e^{\frac{0.1996}{0.025}} - \frac{1}{0.0497}} \right] \\ &= 0.5736 V \end{aligned}$$

Now

$$\begin{aligned} V_{BE} &= V_{Cesat} + V_{BC} \\ &= 0.1996 + 0.5736 \\ &= 0.7732 V \end{aligned}$$

5.51

Eq (5.49)

$$V_{CEsat} = V_T \ln \left[\frac{1 + \frac{\beta_{forced} + 1}{\beta_R}}{1 - \beta_{forced}/\beta_F} \right]$$

For E grounded and C open: $\beta_{forced} = 0$

$$\therefore 60 = 25 \ln \left[\frac{1 + \frac{1}{\beta_R}}{1 - 0} \right]$$

$$\ln \left(1 + \frac{1}{\beta_R} \right) = \frac{60}{25} = 2.4$$

$$\beta_R = \underline{\underline{0.01}}$$

For C grounded and E open

$$\beta_{forced} = 0 \quad \beta_R^* = \beta_F \quad \beta_F^* = \beta_R$$

$$\therefore 1 = 25 \ln \left[\frac{1 + \frac{0+1}{\beta_F}}{1 - 0} \right]$$

$$\ln \left(1 + \frac{1}{\beta_F} \right) = \frac{1}{25}$$

$$\beta_F = \underline{\underline{24.5}}$$

Check:

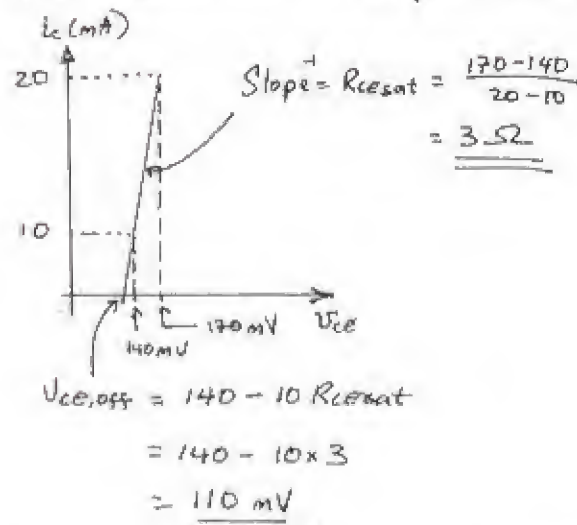
$$-(-1) = 25 \ln \left[\frac{1 + \frac{1}{24.5}}{1 - 0} \right] = 1 \text{ mV}$$

5.52

Information given (where $\beta_{forced} = I_C/I_B$)

I_B (mA)	I_C (mA)	β_{forced}	V_{CEsat} (mV)
0.5	10	20	140
0.5	20	40	170

Given information displayed pictorially



Inserting the given data into Eq (5.49) gives the following two equations

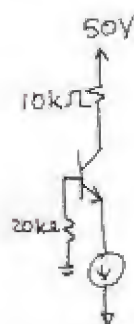
$$140 = 25 \ln \left[\frac{1 + \frac{21}{\beta_R}}{1 - 20/\beta_F} \right] \quad (1)$$

$$170 = 25 \ln \left[\frac{1 + \frac{41}{\beta_R}}{1 - 40/\beta_F} \right] \quad (2)$$

which can be solved together to yield:

$$\beta_F = \underline{\underline{68.2}} \quad \beta_R = \underline{\underline{0.111}}$$

5.53



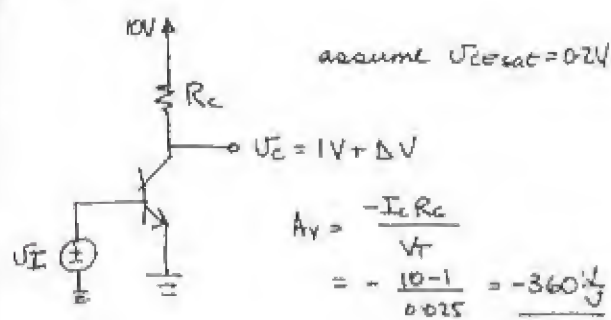
$$B V_{CE0} = 30V$$

$$V_B = \frac{50 - 30}{30} \times 20 = \underline{\underline{13.3V}}$$

$$V_C = 13.3 + 30 = \underline{\underline{43.3V}}$$

$$V_E = 13.3 - 0.7 = \underline{\underline{12.6V}}$$

5.54



At saturation $V_{CEsat} = 0.3V$

$$\therefore V_C = 1 + \Delta V = 0.3$$

$$\Delta V = -0.7V$$

$$\therefore V_O = 0.3V \quad I_C = \frac{10-0.3}{R_C}$$

$$\frac{I_{C2}}{I_{C1}} = \frac{9.7/R_C}{(10-1)/R_C} = e^{\Delta V/V_T}$$

\therefore Maximum input signal

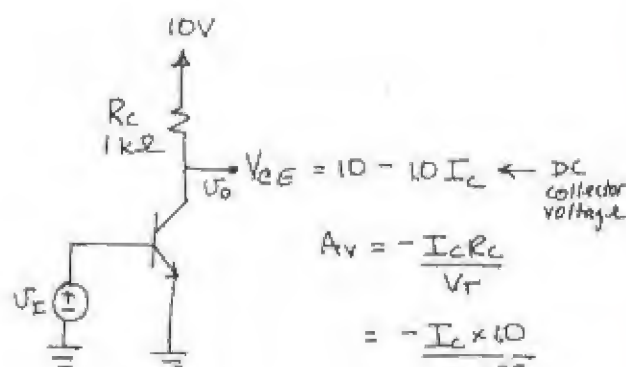
$$\Delta V = 0.025 \ln \frac{9.7}{9} = \underline{\underline{1.87mV}}$$

If we assume linear operation right to saturation we can use the gain A_v to calculate the maximum input swing. Thus for an output swing

$\Delta V_O = 0.8$ we have

$$\Delta V_i = \frac{-\Delta V_O}{A_v} = \frac{-0.7}{-360} = \underline{\underline{1.94mV}}$$

5.55



- Assuming the output voltage $V_O = 0.3V$ is the lowest V_{CE} to stay out of saturation.

$$\therefore V_O = 0.3 = 10 - I_C R_C$$

$$= 10 - I_C R_C + \Delta V_O$$

$$\Delta V_O = -10 + 0.3 + I_C \times 1 (2)$$

- Max output voltage before the transistor is cut off

$$V_{CE} + \Delta V_O = V_{CC}$$

$$\Delta V_O = V_{CC} - V_{CE}$$

$$= 10 - 10 + 10I_C$$

$$= 10I_C (3)$$

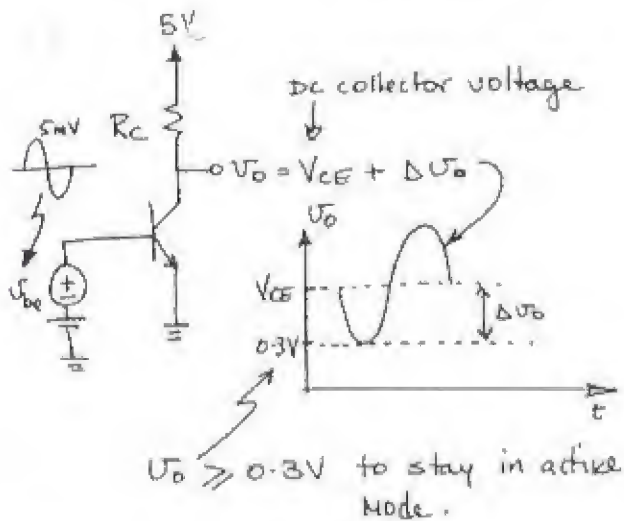
Use (1) to calculate the gain and (2), (3) to calculate the output limits in order to stay in active mode for a particular bias current I_C .

$$I_C (mA) \quad A_v (V/V) \quad \Delta V_O (V)$$

1	-40	-8 to 1
2	-80	-7 to 2
5	-200	-4.7 to 5
8	-320	-1.7 to 8
9	-360	-0.7 to 9

5.56

Since we are assuming linear operation we don't have to go to $i_c = I_s e^{V_{BE}/V_T}$ equation.



$$A_v = - \frac{I_C R_C}{V_T} = - \frac{V_{CE} - V_{CEs}}{V_T}$$

On the verge of saturation

$$V_{CE} - \Delta V_{CE} = 0.3V \quad \text{for linear operation}$$

$$V_{CE} - |A_v V_{be}| = 0.3$$

$$(5 - I_c R_c) - A_v \times 5 \times 10^{-3} = 0.3$$

$$5 - |A_v V_T| - |A_v \times 5 \times 10^{-3}| = 0.3$$

$$|A_v(0.025 + 0.005)| = 5 - 0.3$$

$|A_v| = 156.67$ Note A_v is negative.

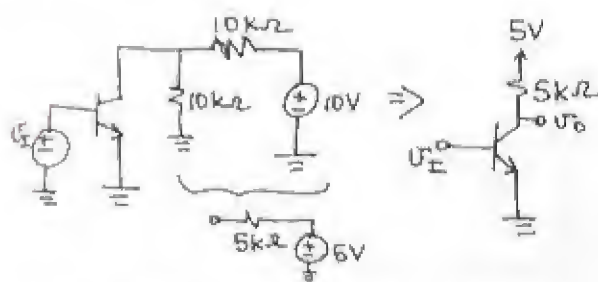
$$\therefore A_V = -156.67 \text{ V/V}$$

Now we can find the dc collector voltage. Refer to sketch of the output voltage, we see that

$$|\Delta V_0| = |A_v \times 0.005|$$

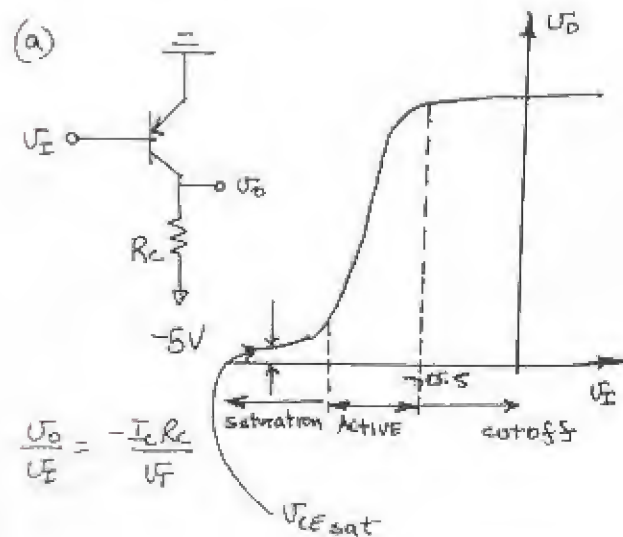
$$\therefore V_{CE} = 0.3 + |A_v| 0.005$$
$$= \underline{1.08V}$$

5.57



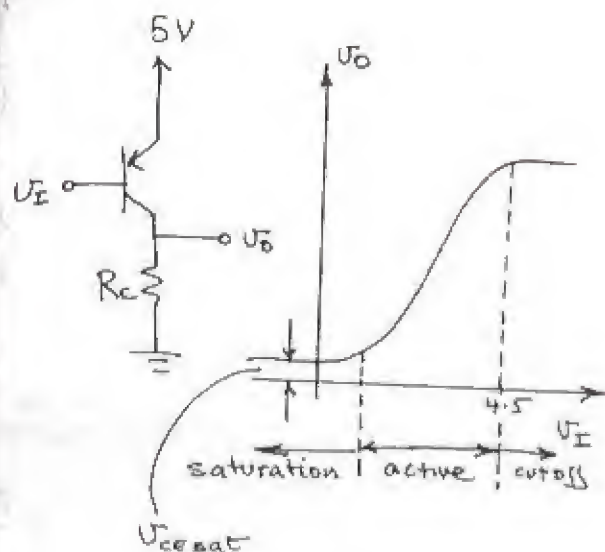
$$\frac{V_o}{V_i} = -\frac{I_c R_c}{V_T} = -\frac{0.5 \times 5}{0.026} = -100 \text{ V/V}$$

5-58



CONT.

(b)



5.89

Including the Early effect we note that:

$$I_C = I_S e^{V_{BE}/V_T} \left(1 + V_{CE}/V_A \right)$$

Also, note $I_C = I_S e^{V_{BE}/V_T}$ Eq (5.38b) is the value of the collector current with the Early voltage neglected.

Starting with the voltage at the collector we have:

$$\begin{aligned} V_O &= V_{CC} - I_C R_C \\ &= V_{CC} - R_C I_S e^{V_{BE}/V_T} \left(1 + \frac{V_{CE}}{V_A} \right) \end{aligned}$$

Take derivative to get gain A_v

$$\begin{aligned} A_v &= \frac{\partial V_O}{\partial V_{BE}} \\ &= -R_C I_S \left[\frac{e^{V_{BE}/V_T}}{V_T} \left(1 + \frac{V_{CE}}{V_A} \right) + \frac{e^{V_{BE}/V_T}}{V_A} \frac{\partial V_{CE}}{\partial V_{BE}} \right] \end{aligned}$$

$$A_v = -\frac{R_C I_S}{V_T} e^{V_{BE}/V_T} \left[1 + \frac{V_{CE}}{V_A} + \frac{V_T}{V_A} \frac{\partial V_{CE}}{\partial V_{BE}} \right]$$

$$= -\frac{R_C I_C}{V_T} \left[1 + \frac{V_{CE}}{V_A} + \frac{V_T}{V_A} A_v \right]$$

$$-A_v \left[\frac{1}{\frac{R_C I_C}{V_T}} + \frac{V_T}{V_A} \right] = 1 + \frac{V_{CE}}{V_A} = \frac{V_A + V_{CE}}{V_A}$$

$$-A_v \left[\frac{V_A + R_C I_C}{\frac{R_C I_C V_A}{V_T}} \right] = \frac{V_A + V_{CE}}{V_A}$$

$$\begin{aligned} -A_v \frac{R_C I_C}{V_T} &= \frac{V_A}{V_A + R_C I_C} \times \frac{V_A + V_{CE}}{V_A} \\ &= \frac{V_A + V_{CE}}{V_A + R_C I_C} \quad \div \text{top \& bottom by } V_A + V_{CE} \end{aligned}$$

$$= \frac{1}{\frac{V_A}{V_A + V_{CE}} + \frac{R_C I_C}{V_A + V_{CE}}}$$

This term is ≈ 1
 $\because V_A \gg V_{CE}$

$$\therefore A_v \approx \left[\frac{-R_C I_C / V_T}{\left(1 + \frac{R_C I_C}{V_A + V_{CE}} \right)} \right]$$

Q.E.D.

For $V_{CC} = 5V$ $V_{CE} = 2.5V$ $V_A = 100V$

Ignoring the Early Voltage:

$$A_v = \frac{-I_C R_C}{V_T} = \frac{V_{CC} - V_{CE}}{V_T} = \frac{5 - 2.5}{0.025} = \underline{\underline{100V/V}}$$

With the Early Voltage

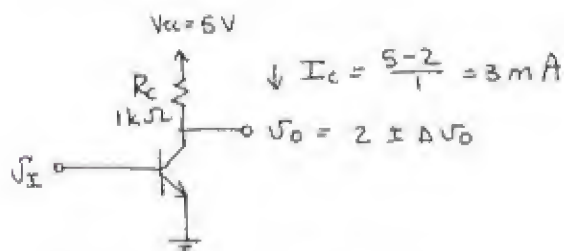
$$A_v \approx \frac{-I_C R_C / V_T}{1 + \frac{R_C I_C}{V_A + V_{CE}}}$$

COWT.

But $V_{CE} = 0.5V$ & $\frac{I_C R_C}{V_T} = 100$ as shown above.

$$A_v = \frac{-100}{1 + \frac{2.5}{100+2.5}} = -97.7 V/V$$

5.60



Small signal voltage gain

$$A_v = -\frac{I_C R_C}{V_T} = \frac{-3 \times 1}{0.025} = -120 V/V$$

If we assume linear operation around the bias point we can use A_v .

$$\Delta v_o = -120 \times 5 \times 10^{-3} = -0.6V \quad \text{for } \Delta v_{BE} = 5mV$$

$$\Delta v_o = 120 \times 5 \times 10^{-3} = 0.6V \quad \text{for } \Delta v_{BE} = -5mV$$

Using the transistor exponential characteristics as in Example 5.2:

For $\Delta v_{BE} = 5mV$:

$$\frac{I_C}{3mA} = e^{\Delta v_{BE}/V_T} = e^{5/25}$$

$$I_C = 3.66mA$$

$$V_o = 5 - 3.66 = 1.34V$$

$$\Delta v_o = 1.34 - 2 = -0.66V$$

For $\Delta v_{BE} = -5mV$

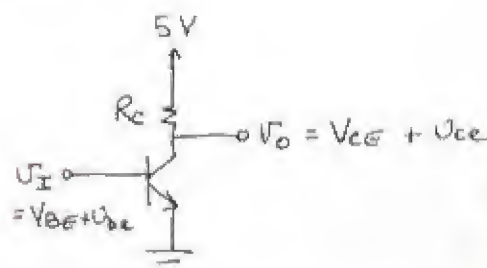
$$I_C = 3 \times e^{-5/25} = 2.46mA$$

$$V_o = 5 - 2.46 \times 1 = 2.54V$$

$$\Delta v_o = 2.54 - 2 = 0.54V$$

$\Delta v_{BE} (mV)$	$\Delta v_o (V)$ Exponential	$\Delta v_o (V)$ Linear
+0.5	-0.66	-0.6
-0.5	+0.54	+0.6

5.61



(a) For maximum gain you would bias at the largest current since $A_v = -I_C R_C / V_T$. This also means you would bias at the edge of saturation

$$A_v = \frac{-V_{CC} - V_{CEsat}}{V_T}$$

$$= \frac{-5 - 0.3}{0.025}$$

$$= -188 V/V$$

However any signal swing at the output would automatically drive it into saturation.

(b) for $A_v = -100 V/V$

$$A_v = \frac{V_{CC} - V_{CE}}{V_T} = \frac{5 - V_{CE}}{V_T} = 100$$

$$V_{CE} = 2.5V$$

CONT.

(c) For a dc collector current of 0.5mA

$$R_c = \frac{5-2.5}{0.5} = \underline{\underline{5\text{ k}\Omega}}$$

(d) $I_s = 10^{-15}\text{A} \Rightarrow$

$$I_c = I_s e^{V_{BE}/V_T}$$

$$0.5 \times 10^{-3} = 10^{-15} e^{V_{BE}/0.025}$$

$$V_{BE} = \underline{\underline{0.673\text{V}}}$$

(e) If we assume linear operation we can use A_v to find the output change for $V_{be} = 5\text{mV}$

$$V_{ce} = A_v V_{be} = -100 \times 0.005$$

$$= -0.5\text{V} \sim \text{peak sine wave.}$$

\therefore the output is a 0.5V p sine wave

(f) for $V_{ce} = 0.5$

$$i_c = \frac{0.5}{5} = \underline{\underline{0.1\text{mA peak}}}$$

This current is superimposed on I_c .

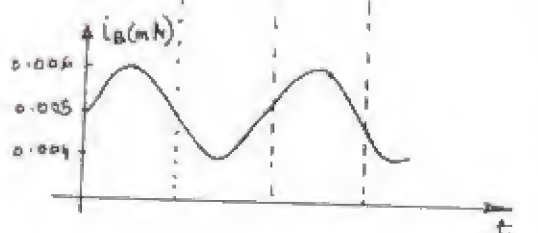
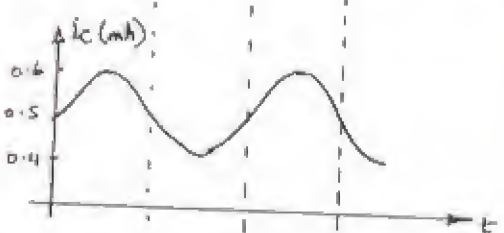
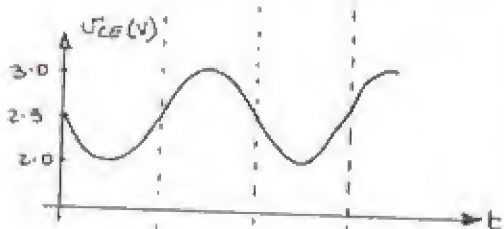
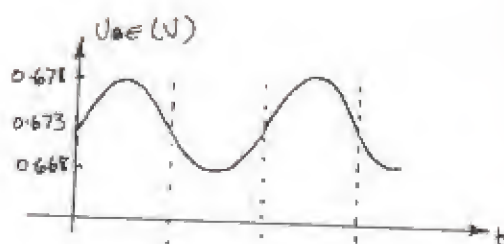
(g) $I_B = I_c / \beta = \frac{0.5}{100} = \underline{\underline{0.005\text{mA}}}$

$$i_b = \frac{i_c}{\beta} = \frac{0.1}{100} = \underline{\underline{0.001\text{mA p}}}$$

(h) $r_{in} = \frac{V_{be}}{i_b} = \frac{0.005}{0.001 \times 10^{-3}}$

$$= \underline{\underline{5\text{ k}\Omega}}$$

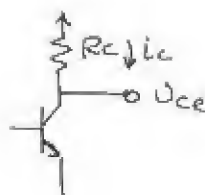
(i) See sketches that follow:



5.62

$E_Q (5.56)$

$$A_v = \frac{V_{ce}}{V_{be}} = -\frac{I_c R_c}{V_T}$$



But $V_{ce} = -i_c R_c$

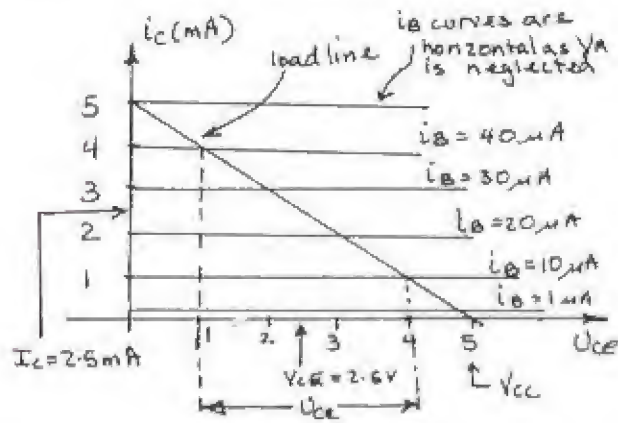
$$\therefore -\frac{i_c R_c}{V_{be}} = -\frac{I_c R_c}{V_T}$$

Now $g_m = \frac{\text{output current}}{\text{input voltage}} = \frac{i_c}{V_{be}}$

$$\therefore g_m R_c = \frac{I_c R_c}{V_T}$$

$$\underline{\underline{g_m = I_c / V_T}}$$

5.63



For I_B varying from $10 \mu A$ to $40 \mu A$, i_c varies from 1 mA to 4 mA ($\beta = 100$), and $V_{CE} = V_{CC} - R_C i_c$ varies from 4 V to 1 V . Thus the peak-to-peak collector voltage swing is

$$V_{CE} = 3 \text{ V p-p}$$

$$\text{For } V_{CE} = \frac{1}{2} V_{CC} = 2.5 \text{ V}$$

$$I_C = 2.5 \text{ mA}$$

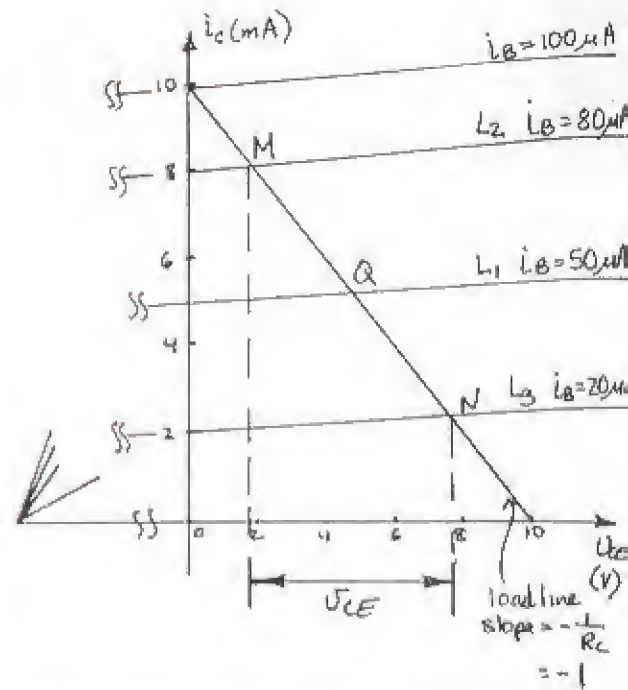
$$\therefore I_B = \frac{2.5}{100} = 25 \mu A$$

$$\begin{aligned} V_{BB} &= V_{BE} + I_B R_B \\ &= 0.7 + 0.025 \times 100 \\ &= 3.2 \text{ V} \end{aligned}$$

5.64

See the graphical construction that follows. For this circuit:

$$\begin{aligned} V_{CC} &= 10 \text{ V} & \beta &= 100 \\ R_C &= 1 \text{ k}\Omega & V_A &= 100 \text{ V} \\ I_B &= 50 \mu A \text{ - dc bias} & i_c &= \beta I_B \text{ at } V_{CE} = 0 \\ \therefore I_C &= 50 \times 100 \\ &= 5 \text{ mA - dc bias} \end{aligned}$$



Given the base bias current of $50 \mu A$, the dc or bias point of the collector current I_C & voltage V_{CE} can be found from the intersection of the load line & the transistor line L_1 of $I_B = 50 \mu A$. Specifically:

$$\begin{aligned} \text{Eq of } L_1 \Rightarrow i_c &= I_C (1 + V_{CE}/V_A) \\ &= 5 (1 + V_{CE}/100) \\ &= 5 + 0.05 V_{CE} \end{aligned}$$

$$\begin{aligned} \text{Eq of loadline} \Rightarrow i_c &= \frac{V_{CC} - V_{CE}}{R_C} \\ &= 10 - V_{CE} \end{aligned}$$

$$\begin{aligned} \therefore 10 - V_{CE} &= 5 + 0.05 V_{CE} \\ V_{CE} &= V_{CE} = 4.76 \text{ V} \end{aligned}$$

$$I_C = i_c = 10 - V_{CE} = 5.24 \text{ mA}$$

Now for a signal of $30 \mu A$ peak superimposed on $I_B = 50 \mu A$, the operating point moves along the

CONT.

load line between points N and M. To obtain the coordinates of point M, we solve the load line and line L_2 to find the intersection M and the load line and line L_3 to find N:

For Point M:

$$i_c = 8 + \frac{8}{100} V_{CE} \quad \& \quad i_c = 10 - V_{CE}$$

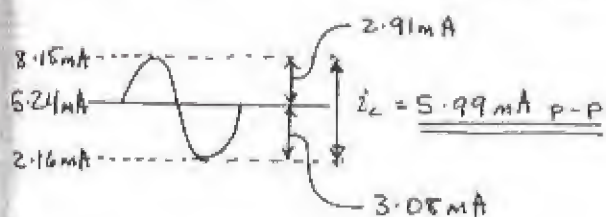
$$\therefore i_{c|M} = 8.15 \text{ mA} \quad V_{CE|M} = 1.85 \text{ V}$$

For Point N:

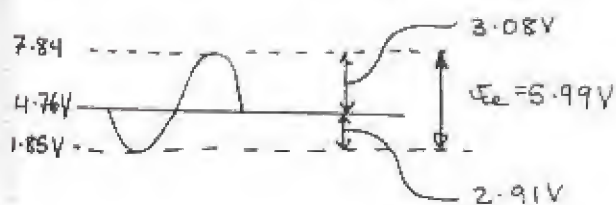
$$i_c = 2 + 0.02 V_{CE} \quad \& \quad i_c = 10 - V_{CE}$$

$$V_{CE|N} = 7.84 \text{ V} \quad i_{c|N} = 2.16 \text{ mA}$$

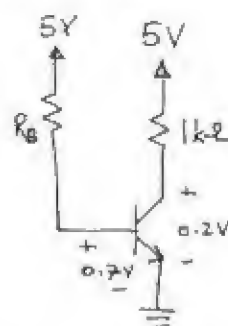
Thus the collector current varies as follows



And the collector voltage varies as:



5.65



$$\frac{\beta_F}{\beta_{forced}} = \text{overdrive factor} = 10$$

$$\therefore \beta_{forced} = \frac{\beta_F}{10} = \frac{20}{10} = 2$$

for $V_{CEsat} = 0.2 \text{ V}$

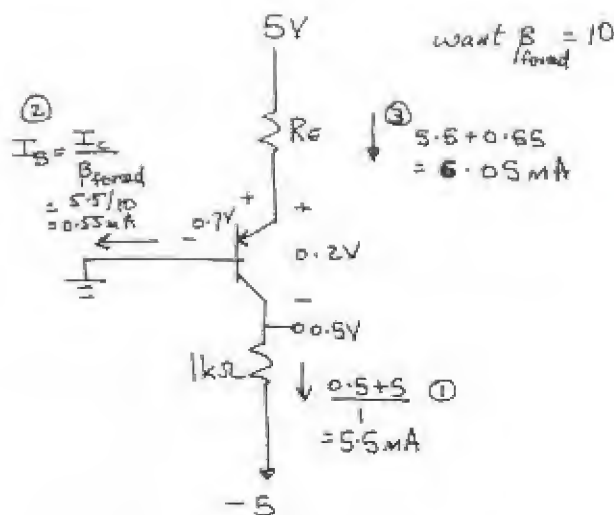
$$5 - I_{ceat} \times 1 = 0.2$$

$$I_{ceat} = 5 - 0.2 = 4.8 \text{ mA}$$

$$I_B = \frac{I_{ceat}}{\beta_{forced}} = \frac{4.8}{2} = 2.4 \text{ mA}$$

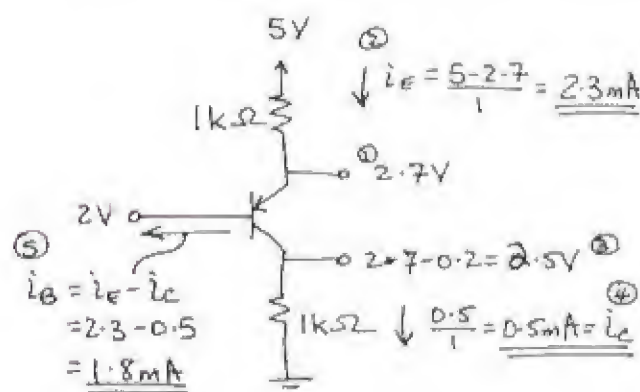
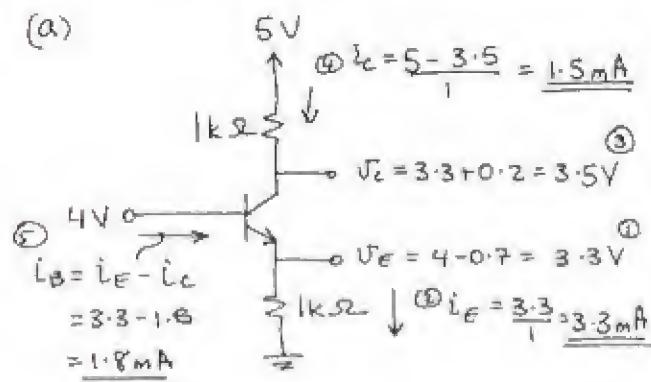
$$\therefore R_B = \frac{5 - 0.7}{2.4} = \frac{4.3}{2.4} = 1.8 \text{ k}\Omega$$

5.66

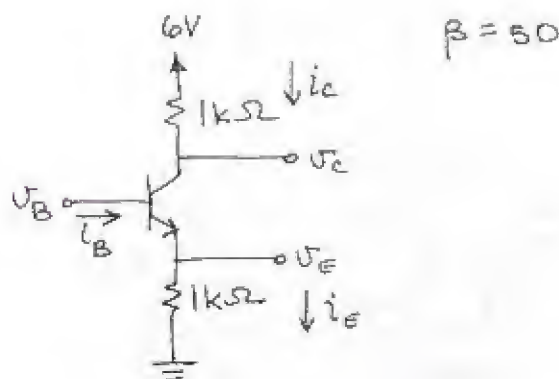


$$R_E = \frac{5 - 0.7}{6.05} = 710 \Omega$$

5.67



5.68



Since conduction does not start until $V_{BE} = 0.5V$, I_c & I_e are essentially 0 for $V_B \leq 0.5V$

For:

$$V_B = 1V$$

$$V_E = 1 - 0.3 = 0.7V$$

$$I_E = \frac{0.3}{1} = 0.3mA$$

$$I_c = \frac{\beta}{\beta + 1} I_E$$

$$= \frac{50}{51} \times 0.3$$

$$= 0.2941mA$$

$$V_c = 6 - 0.2941$$

$$= 5.71V$$

$$I_B = I_E - I_c = \left(\frac{I_E}{\beta} \right) \rightarrow I_B = 2.3 - 2.25 = 0.0059mA$$

$$V_B = 3V$$

$$V_E = 3 - 0.7 = 2.3V$$

$$I_E = \frac{2.3}{1} = 2.3mA$$

$$I_c = \frac{\beta}{\beta + 1} I_E$$

$$= \frac{50}{51} \times 2.3$$

$$= 2.2549$$

$$V_c = 6 - 2.25$$

$$= 3.75V$$

let saturation begin at $V_B = x$
 - at saturation starting
 $V_{CE} = 0.4V$

$$V_c = x - 0.4 \Rightarrow I_c = \frac{6 - x + 0.4}{1}$$

$$V_E = x - 0.7 \Rightarrow I_E = \frac{x - 0.7}{1}$$

Since we are still in active mode $I_c = \frac{50}{51} I_E$

$$(6.4 - x) = \frac{50}{51} (x - 0.7)$$

$$101x = 361.4$$

$$\therefore x = V_B = 3.58V$$

$$I_c = 6 - x + 0.4 = 2.82mA$$

$$I_B = \frac{I_c}{\beta} = \frac{2.82}{50} = 0.056mA$$

For $V_B = 4V$ and $6V$, the transistor is in saturation. Assume $V_{BE} = 0.7V$
 $V_{CEsat} = 0.7 - 0.6 = 0.1V$

CONT.

For:

$$V_B = 4V$$

$$V_E = 4 - 0.7 = 3.3V$$

$$I_E = \frac{3.3}{1} = 3.3mA$$

$$V_C = 3.3 + 0.1 = 3.4V$$

$$I_C = \frac{6 - 3.4}{1} = 2.6mA$$

$$I_B = I_E - I_C = 3.3 - 2.6 = 0.7mA$$

$$V_B = 6V$$

$$V_E = 6 - 0.7 = 5.3V$$

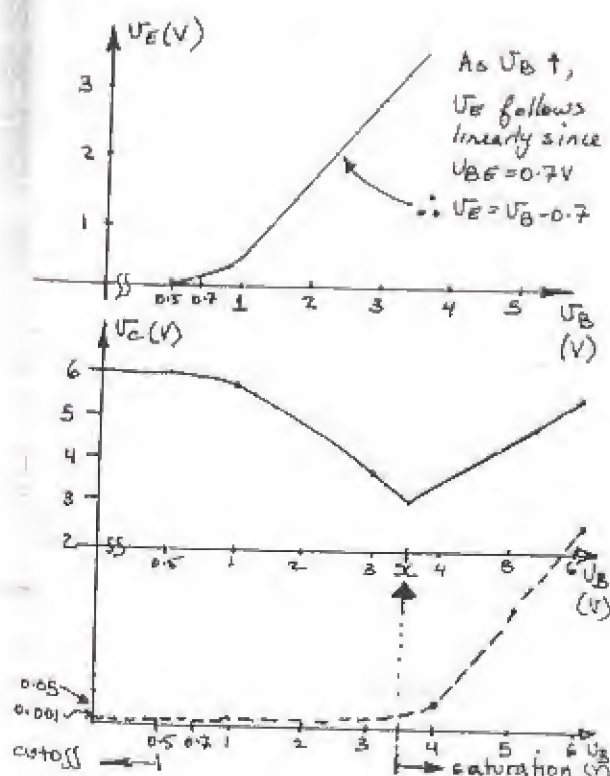
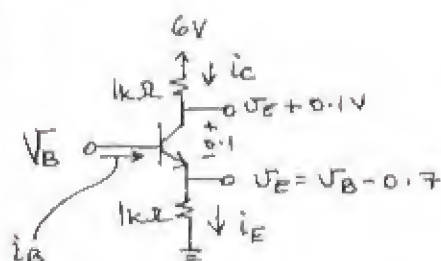
$$I_E = \frac{5.3}{1} = 5.3mA$$

$$V_C = 5.3 + 0.1 = 5.4V$$

$$I_C = \frac{6 - 5.4}{1} = 0.6mA$$

$$I_B = 5.3 - 0.6 = 4.7mA$$

CIRCUIT IN SATURATION:



Notice for $V_B \leq 0.5V$ the transistor is essentially cutoff. Then at saturation, as V_B increases, both V_E & V_C increases linearly. This occurs as $V_{BE} = 0.7V$ & $V_{CE} = 0V$ in saturation.

5.69

(a) $V_B = 2V$

$$V_E = 2 - 0.7 = 1.3V$$

$$I_E = \frac{V_E}{1} = 1.3mA$$

$$I_C \approx 1.3mA$$

$$V_C = 5 - 1.3 = 3.7V$$

(b) $V_B = 1V$

$$V_E = 1 - 0.7 = 0.3V$$

$$I_E \approx I_C = 0.3mA$$

$$V_C = 5 - 0.3 = 4.7V$$

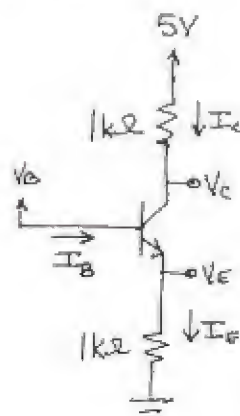
(c) $V_B = 0V$ - cutoff

$$V_E = 0V$$

$$I_E = 0A$$

$$V_C = 5V$$

5.70



β - high

The transistor stays in active mode until $V_{CB} = -0.4V$

$$\therefore V_C - V_B = -0.4V$$

$$\therefore I_C = I_E$$

$$\frac{5 - (V_B - 0.4)}{1} = \frac{V_B - 0.7}{1}$$

$$5.7 + 0.4 = 2V_B$$

$$V_B = 3.05V$$

CONT.

For operation with $\beta_{forced} = 1 \Rightarrow$

$$\beta_{forced} = \frac{I_{csat}}{I_B} = 1 \quad \left\{ \begin{array}{l} \text{assume} \\ V_{CE} = 0.2V \\ V_{CB} = -0.5V \end{array} \right.$$

$$\therefore I_{csat} = I_B$$

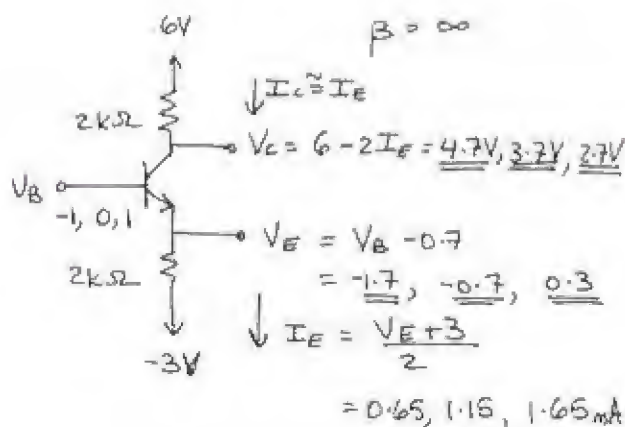
$$I_E = I_{csat} + I_B = 2I_{csat}$$

$$\frac{V_B - 0.7}{1} = 2 \times \frac{5 - (V_B - 0.5)}{1}$$

$$V_B - 0.7 = 2(5.5 - V_B)$$

$$V_B = \underline{\underline{3.9V}}$$

5.71



- Want V_B when $I_E = \frac{1}{10} \times 1.65mA$
 $= 0.165mA$

$$V_E = -3 + 0.165 \times 2 = \underline{\underline{-2.67V}}$$

$$V_B = V_E + 0.7 = \underline{\underline{-2.07V}}$$

- Want V_B at the edge of conduction
 At the edge of conduction assume $V_{BE} = 0.5V$

$$\therefore V_B - 0.5 - 2I_E + 3 = 0 \leftarrow I_E = 0$$

$$V_B = \underline{\underline{-2.5V}}$$

at edge
of conduction

$$V_E = V_B - 0.5 = \underline{\underline{-3V}}$$

$$I_C \approx 0A \quad \therefore V_C = \underline{\underline{6V}}$$

At saturation assume $V_{CE} = 0.2V$
 $V_{CB} = -0.5V$

$$\therefore I_E = \frac{V_B - 0.7 + 3}{2} \approx I_C = \frac{6 - (V_B - 0.5)}{2}$$

$$\therefore V_B + 2.3 = 6.5 - V_B$$

$$V_B = \underline{\underline{2.1V}}$$

$$V_E = 2.1 - 0.7 = \underline{\underline{1.4V}} \quad V_C = V_B - 0.5 = \underline{\underline{1.6V}}$$

- Want V_B at $\beta_{forced} = 2$, $V_{CE} = 0.2V$
 $V_{CB} = -0.5V$

$$\beta_{forced} = \frac{I_{csat}}{I_B} = 2$$

$$I_E = I_B + I_{csat} = \frac{I_{csat}}{2} + I_{csat} = \frac{3}{2} I_{csat}$$

$$V_E = V_B - 0.7 = -3 + 2I_E = -3 + 3I_{csat}$$

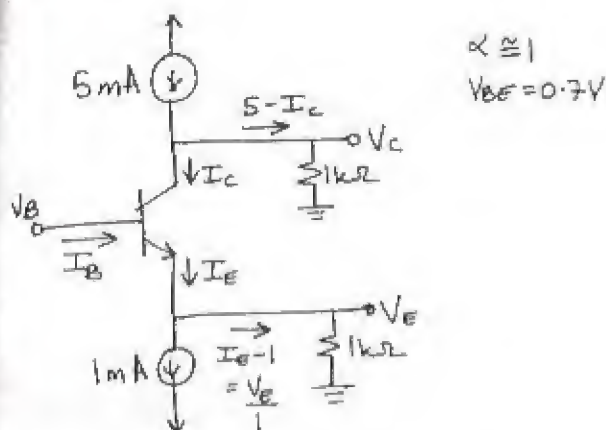
$$I_{csat} = \frac{2.3 + V_B}{3}$$

$$I_C = \frac{V_{CC} - (V_B - 0.5)}{2} = I_{csat}$$

$$6.5 - V_B = \frac{2}{3}(2.3) + \frac{2}{3}V_B$$

$$V_B = \frac{6.5 - \frac{2(2.3)}{3}}{1\frac{2}{3}} = \underline{\underline{2.98V}}$$

5.72



Under normal conduction $V_B = 0V$

$$V_E = 0 - 0.7 = -0.7V$$

$$I_E = 1 - 0.7 = 0.3mA \approx I_C$$

$$V_C = (5 - 0.3) \cdot 1 = 4.7V$$

At cutoff ~ all of the current in the 1mA source is supplied through R_E
 $V_{BE} = 0.6V$

$$\therefore V_E = -1 \times 1 = -1V \quad \& \quad I_E = I_C = 0$$

$$\therefore V_B = V_E + 0.5 = -1 + 0.5 = -0.5V$$

-For Saturation $V_{CE} = 0.2V$, $V_{CB} = -0.5V$

$$V_C = V_E + 0.2$$

$$I_C = 5 - V_C/1 = 5 - (V_E - 0.2)$$

$$= 5.2 - V_E$$

$$I_E = \frac{V_E}{1} + 1$$

At the edge of saturation
 $I_E \approx I_C$ still!

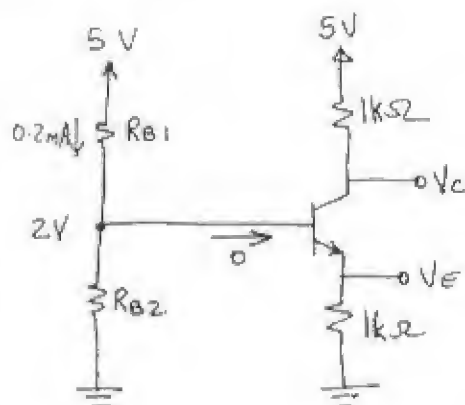
$$\therefore 5.2 - V_E = V_E + 1$$

$$V_E = 4.2/2 = 2.1V$$

$$V_B = V_E + 0.7 = 2.8V$$

$$V_C = V_E + 0.2 = 2.3V$$

5.73



For $\beta = \infty$

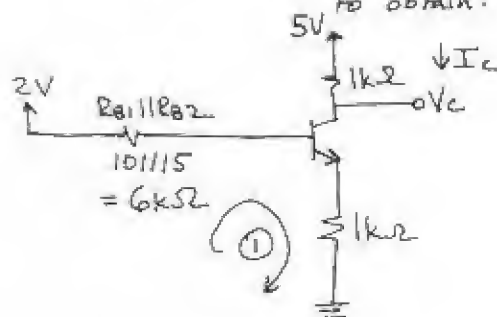
$$\frac{5}{R_{B1} + R_{B2}} = 0.2 \quad \& \quad \frac{R_{B2}}{R_{B1} + R_{B2}} \cdot 5 = 2$$

$$R_{B1} + R_{B2} = 25k\Omega$$

$$\Rightarrow \frac{R_{B2}}{25} \times 5 = 2$$

$$R_{B2} = 10k\Omega \quad R_{B1} = 15k\Omega$$

Now for $\beta = 100$, use Thevenin's to obtain:



$$\text{Loop ①} \quad 2 - 6 \left(\frac{I_E}{\beta + 1} \right) - 0.7 - I_E(1) = 0$$

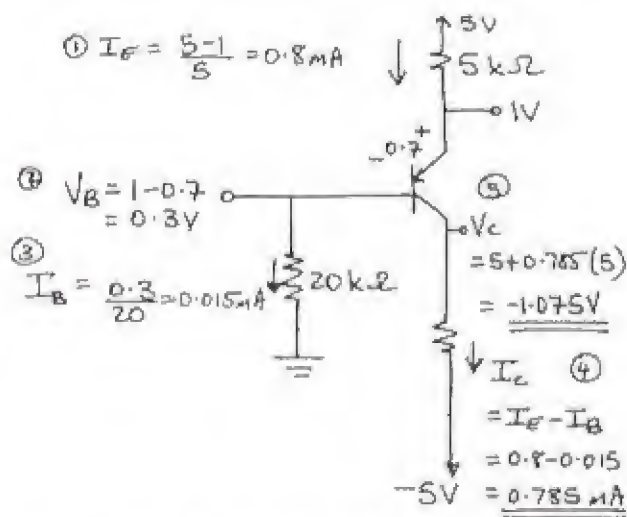
$$I_E = 1.29mA$$

CONT.

$$I_c = \frac{100}{101} I_E = \frac{100}{101} \times 1.29 = \underline{1.28 \text{ mA}}$$

$$V_c = 5 - 1.28(1) = \underline{3.72 \text{ V}}$$

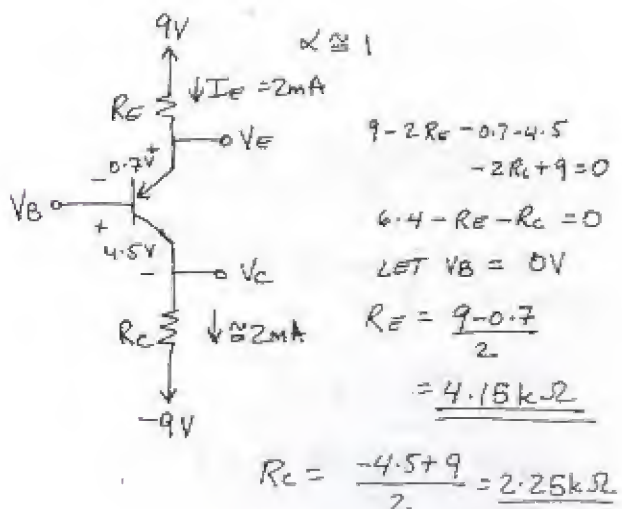
5.74



$$\textcircled{6} \beta = \frac{I_C}{I_B} = \frac{0.785}{0.015} = \underline{52.3}$$

$$\textcircled{7} \alpha = \frac{I_C}{I_E} = \frac{0.785}{0.8} = \underline{0.98}$$

5.75



Using 5% resistor values

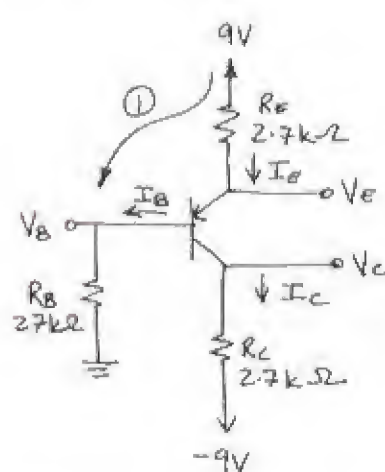
$$R_E = 3.9 \text{ k}\Omega \quad R_C = 2.2 \text{ k}\Omega$$

$$I_E = \frac{9-0.7}{3.9} = \underline{2.12 \text{ mA}}$$

$$V_C = -9 + 2.12 \times 2.2 = -4.3 \text{ V}$$

$$\therefore V_{BC} = \underline{4.3 \text{ V}}$$

5.76



$$\text{Loop ①} \quad 9 - 2.7 I_E - 0.7 - \frac{I_E}{31} R_E = 0$$

$$I_E = 2.3243 \text{ mA}$$

$$V_B = R_B \times I_E / 31 = \underline{2.02 \text{ V}}$$

$$V_E = 9 - 2.7 I_E = \underline{2.72 \text{ V}}$$

$$V_C = -9 + \frac{30}{31} I_E (2.7) = \underline{-2.93 \text{ V}}$$

$$\text{For } R_B = 270 \text{ k}\Omega$$

$$\text{Loop ①} \quad 9 - 2.7 I_E - 0.7 - \frac{R_B}{31} I_E = 0$$

$$I_E = 0.7274 \text{ mA}$$

CONT.

$$V_B = R_B \times \frac{I_E}{31} = \underline{6.34V}$$

$$V_E = 9 - 2.7 I_E = \underline{7.04V}$$

$$V_C = \frac{30}{31} I_E (2.7) - 9 = \underline{-7.10V}$$

To return the voltages to the ones first calculated we have

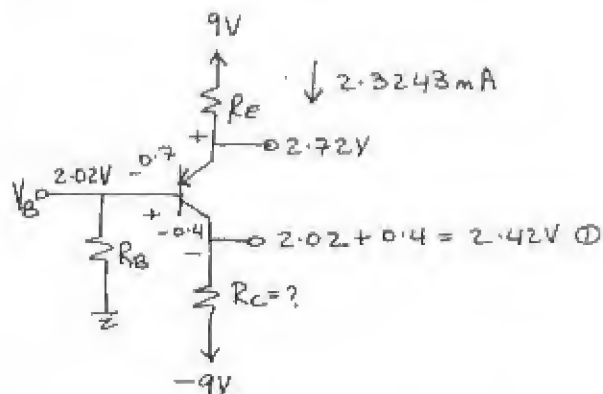
$$\text{Loop ① } \sim I_E = 2.3243 \text{ mA}$$

$$9 - 2.7 I_E - 0.7 - \frac{270}{\beta + 1} I_E = 0$$

$$\beta = \underline{309}$$

5.77

Using the values from the first part of P5.76 and for the edge of saturation $V_{BC} > -0.4V$



CIRCUIT AT THE EDGE OF SATURATION

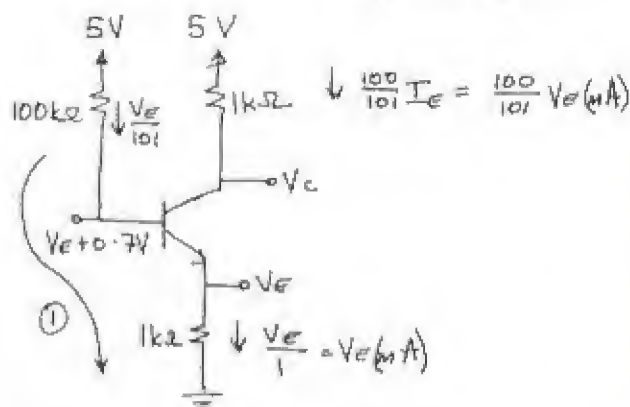
$$I_C = \frac{30}{31} I_E = \frac{30}{31} \times 2.3243$$

$$R_C = \frac{2.42 + 9}{\frac{30}{31} \times 2.3243} = \underline{5.08 k\Omega}$$

5.78

$$\beta = 100$$

(a) $R_B = 100 k\Omega$ - R_E is large assume active mode.



Loop ①

$$5 - \frac{V_E}{101} \times 100 - 0.7 - V_E = 0$$

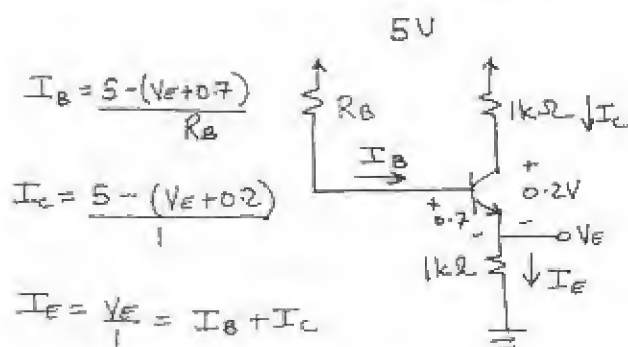
$$V_E = \underline{2.16V}$$

$$V_B = V_E + 0.7 = \underline{2.86V}$$

$$V_C = 5 - 1 \times \frac{100}{101} V_E = \underline{2.86V}$$

Thus the BJT is in active mode as assumed.

(b) $R_B = 10 k\Omega$ - assume saturation



$$\therefore V_E = \frac{4.3 - V_E}{10} + 4.8 - V_E$$

$$10V_E + V_E + 10V_E = 4.3 + 48$$

CONT

$$V_E = \underline{2.49V}$$

$$V_C = 2.49 + 0.2 = \underline{2.69V}$$

$$V_B = V_E + 0.7 = \underline{3.19V}$$

$$\text{Check: } I_C = \frac{5 - 2.69}{1} = 2.31 \text{ mA}$$

$$I_B = \frac{5 - 3.19}{10} = 0.181 \text{ mA}$$

$$\frac{I_C}{I_B} = \frac{2.31}{0.181} = 12.76 < 100$$

Hence
we are in
saturation as
assumed!

(c) $R_B = 1k\Omega$ - expect saturation
- use circuit in (b)

$$I_B = \frac{5 - (V_E + 0.7)}{R_B} = \frac{4.3 - V_E}{1}$$

$$I_C = \frac{5 - (V_E + 0.2)}{1} = \frac{4.8 - V_E}{1}$$

$$I_E = I_B + I_C = V_E$$

$$4.3 - V_E + 4.8 - V_E = V_E$$

$$V_E = \underline{3V}$$

$$V_B = \underline{3.7V}$$

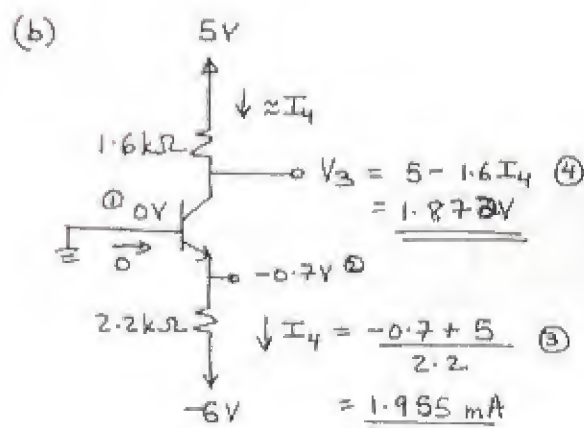
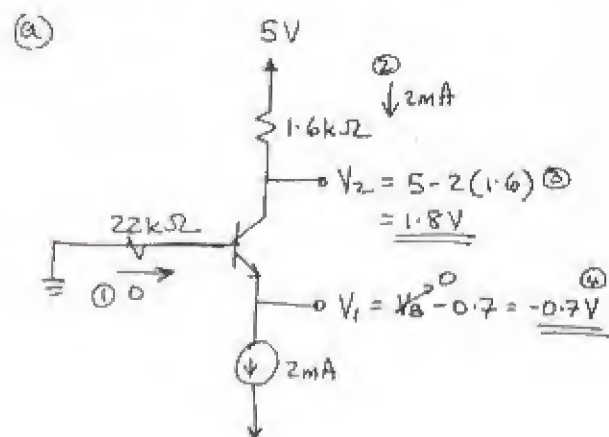
$$V_C = \underline{3.2V}$$

$$\text{Check } I_B = 4.3 - 3 = 1.3 \text{ mA}$$

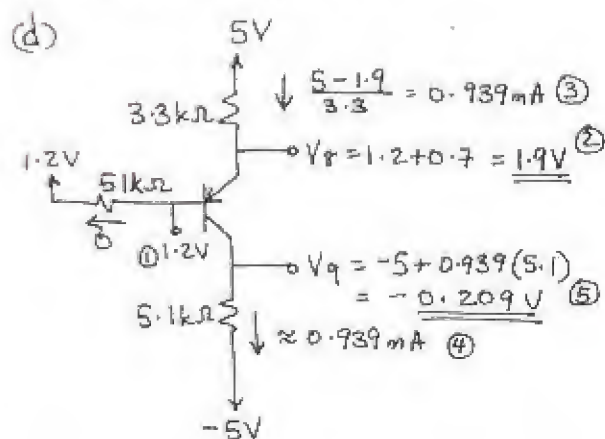
$$I_C = 4.8 - 3 = 1.8 \text{ mA}$$

$$\frac{I_C}{I_B} = \frac{1.8}{1.3} = 1.4 < 100 \therefore \text{SATURATION AS ASSUMED}$$

5.79

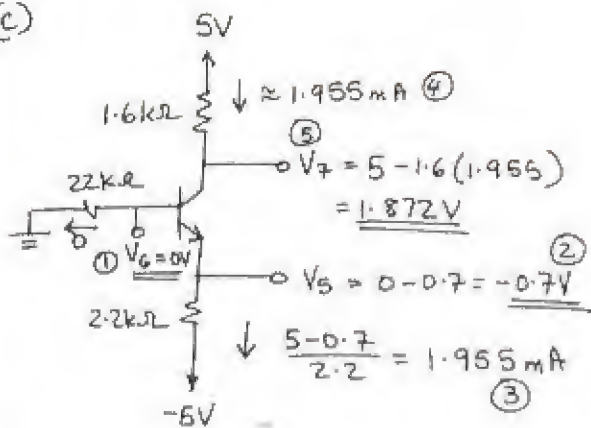


see below for part (c)

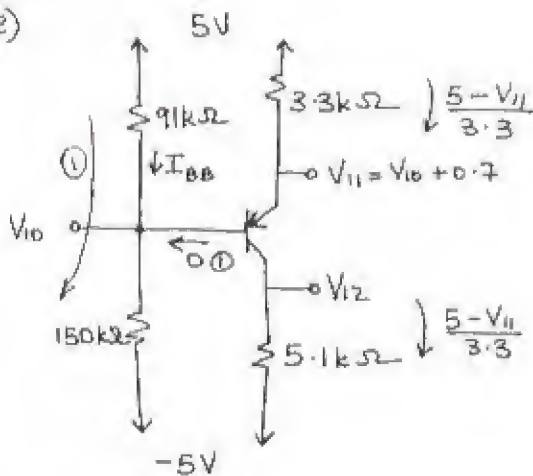


CONT.

(c)



(e)



Loop ①

$$5 - 91I_{BB} - 150I_{BB} + 5 = 0$$

$$I_{BB} = \frac{10}{91 + 150}$$

$$V_{10} = -5 + 150I_{BB}$$

$$= -5 + \frac{150}{91 + 150} \times 10$$

$$= \underline{1.224V}$$

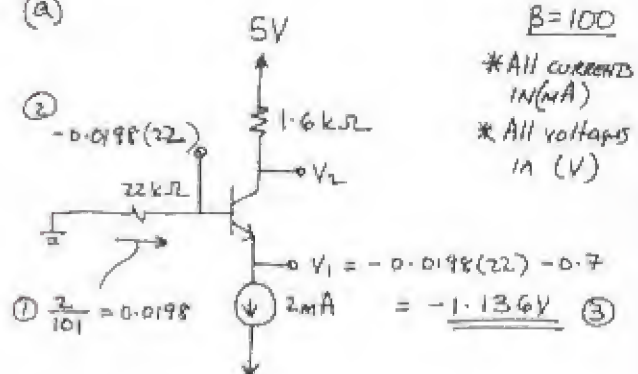
$$V_{11} = V_{10} + 0.7 = \underline{1.924V}$$

$$I_C \approx I_E = \frac{5 - V_{11}}{3.3}$$

$$V_{12} = -5 + \left(\frac{5 - V_{11}}{3.3}\right) 5.1 = \underline{-0.246V}$$

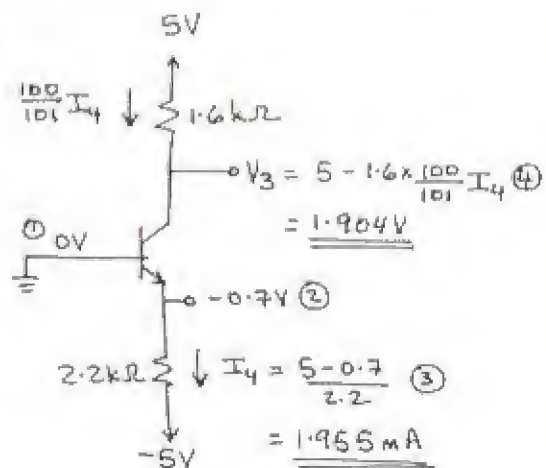
5.80

(a)

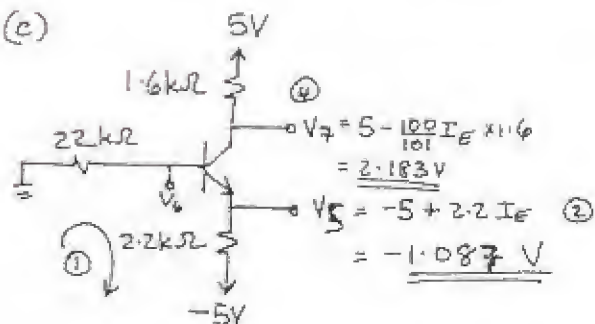


$$V_2 = 5 - 2\left(\frac{100}{101}\right) 1.6 = \underline{1.832V}$$

(b)



(c)



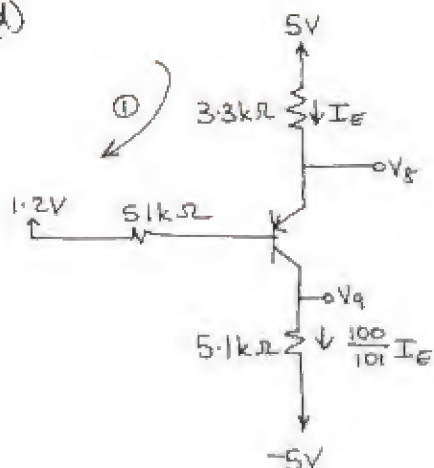
$$\text{Loop ① } 0 - \frac{I_E}{101} 22 - 0.7 - 2.2I_E + 5 = 0$$

$$I_E = 1.778mA$$

$$V_6 = V_3 + 0.7 = \underline{-0.387V}$$

CONT

(d)



Loop ①

$$5 - 3.3 I_E - 0.7 - \frac{I_E}{101} 51 - 1.2 = 0$$

$$I_E = 0.8147 \text{ mA}$$

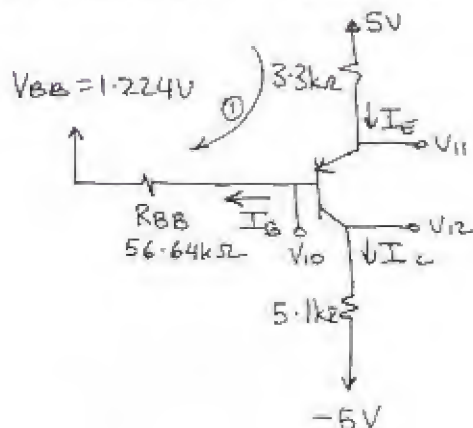
$$V_C = 5 - 3.3 I_E = \underline{2.3114 \text{ V}}$$

$$V_E = -5 + 5.1 \times \frac{100}{101} I_E = \underline{-0.8862 \text{ V}}$$

(e) Use Thevenin's theorem to simplify the bias network:

$$V_{BB} = -5 + \frac{150}{150+91} \times 10 = 1.224 \text{ V}$$

$$R_{BB} = 150 \parallel 91 = 56.64 \text{ k}\Omega$$



Loop ①

$$5 - 3.3 I_E - 0.7 - \frac{I_E}{101} R_{BB} - 1.224 = 0$$

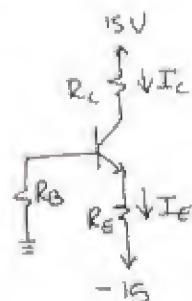
$$I_E = 0.7967 \text{ mA}$$

$$V_{II} = 5 - 3.3 I_E = \underline{2.371 \text{ V}}$$

$$V_{I2} = \frac{100}{101} I_E \times 5.1 - 5 = \underline{-0.977 \text{ V}}$$

$$V_{I0} = V_{II} - 0.7 = \underline{1.67 \text{ V}}$$

5.8

Nominal $\beta = 100$.

Thus,

$$\text{nominal } \alpha = \frac{100}{101} = 0.99$$

nominal $I_E = 1 \text{ mA}$ nominal $I_C = 0.99 \text{ mA}$ nominal $V_C = 5 \text{ V}$

$$\text{Thus, } R_C = \frac{15 - 5}{0.99} = 10.1 \text{ k}\Omega \Rightarrow \underline{10 \text{ k}\Omega}$$

$$I_E = 1 = \frac{15 - 0.7}{R_E + \frac{R_B}{\beta + 1}}$$

$$= \frac{14.3}{R_E + \frac{R_B}{101}}$$

$$\Rightarrow R_E + \frac{R_B}{101} = 14.3 \quad (1)$$

As β varies from 50 to 150, need to limit the variation of I_E to $\pm 10\%$ of 1 mA . One can reason that the maximum variation in I_E occurs for $\beta = 50$ (as opposed to $\beta = 150$). To see this note that when β decreases from 100 to 50 the base current doubles while a change in β from

CONT.

100 to 150 causes the base current to decrease to $\frac{2}{3}$ its nominal value. Thus our decision will be based on imposing the 10% limit for $\beta = 50$.

$$0.9 = \frac{14.3}{R_E + \frac{R_B}{\beta + 1}} = \frac{14.3}{R_E + \frac{R_B}{51}}$$

$$R_E + \frac{R_B}{51} = 15.89 \quad (2)$$

$$(2) - (1) \Rightarrow R_B \left(\frac{1}{51} - \frac{1}{101} \right) = 1.59$$

$$\Rightarrow R_B = 163.8 \text{ k}\Omega \xrightarrow{\text{use}} \underline{\underline{164 \text{ k}\Omega}}$$

Sub into (1) gives

$$R_E = 12.7 \text{ k}\Omega \xrightarrow{\text{use}} \underline{\underline{13 \text{ k}\Omega}}$$

To find the expected range of I_C & V_C corresponding to β variation from 50 to 150 we use

$$I_C = \alpha \frac{14.3}{R_E + \frac{R_B}{\beta + 1}}$$

$$\text{for } \beta = 50 \quad I_C = \frac{50}{51} \times \frac{14.3}{13 + \frac{164}{51}} = \underline{\underline{0.864 \text{ mA}}}$$

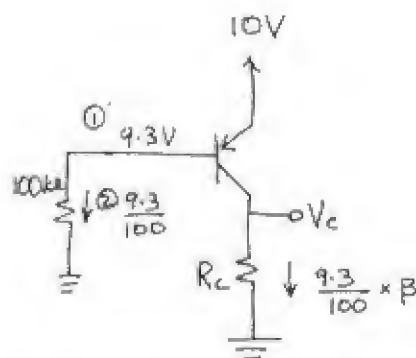
$$V_C = 15 - 0.864 \times 10 = \underline{\underline{6.36 \text{ V}}}$$

$$\text{for } \beta = 150 \quad I_C = \frac{150}{151} \times \frac{14.3}{13 + \frac{164}{151}}$$

$$= \underline{\underline{1.008 \text{ mA}}}$$

$$V_C = 15 - 1.008 \times 10 = \underline{\underline{4.92 \text{ V}}}$$

5.82



$$\text{For } V_C = 5 \text{ V} = \frac{9.3}{100} \times \beta \times R_C \quad \beta = 50$$

$$R_C = \frac{500}{9.3 \times 50} = \underline{\underline{1.08 \text{ k}\Omega}}$$

For $\beta = 100$

$$V_C = \frac{9.3}{100} \times \beta \times R_C = \frac{9.3}{100} \times 100 \times 1.08 = \underline{\underline{10.04 \text{ V}}} \leftarrow V_{BC} = 9.3 - 10.04 = -0.74$$

Since $V_{BC} < -0.4 \text{ V}$ the transistor saturates!

5.83

For $\beta = \infty$ and R open:

$$I_{B1} = I_{B2} = 0, \alpha_1 = \alpha_2 = 1$$

$$I_{D1} = \frac{9 - 0.7}{80K + 40K} = 0.07 \text{ mA}$$

$$V_{B1} = 0.7 + 0.07 \text{ mA} \times 40K = \underline{3.5V}$$

$$V_{E1} = V_{B1} - 0.7V = 3.5 - 0.7 = \underline{2.8V}$$

$$I_{E1} = \frac{2.8V}{2K} = 1.4 \text{ mA}$$

$$I_{E1} = I_{C1} \text{ since } \alpha = 1$$

$$V_{C1} = 9V - 2K \times 1.4 \text{ mA} - 0.7 = \underline{5.5V}$$

$V_{CB} = 2V \rightarrow$ Transistor is in active mode.

$$V_{B2} = V_{C1} = \underline{5.5V}$$

$$V_{E2} = 5.5 + 0.7 = \underline{6.2V}$$

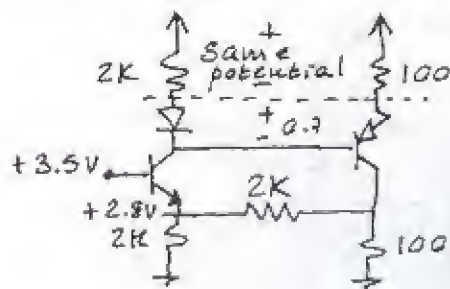
$$I_{E2} = \frac{9 - 6.2}{100} = 28 \text{ mA}$$

$$I_{E2} = I_{C2} \text{ since } \alpha = 1$$

$$\rightarrow V_{C2} = 28 \text{ mA} \times 100\Omega = \underline{2.8V}$$

For $\beta = \infty$ and R connected:

$$\text{Still: } V_{B1} = 3.5V, V_{E1} = 2.8V$$

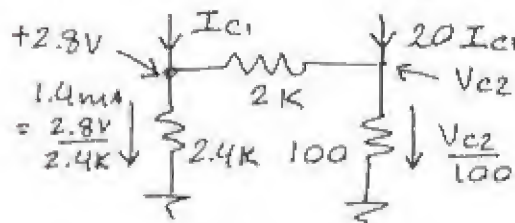


Since the voltage across the top two resistors is equal:

$$I_{C1} \times 2K = I_{E2} \times 100$$

$$I_{E2} = 20 I_{C1}$$

$$\text{also: } I_{C1} = I_{E1} \quad I_{C2} = I_{E2}$$



$$1.4 \text{ mA} - I_{C1} = 20 I_{C1} - \frac{V_{C2}}{100}$$

$$\rightarrow V_{C2} = 100 \times (21 I_{C1} - 1.4 \text{ mA}) \quad (1)$$

also:

$$\frac{V_{C2} - 2.8V}{2K} = 1.4 \text{ mA} - I_{C1}$$

$$\rightarrow V_{C2} = 5.6 - I_{C1} \times 2K \quad (2)$$

Solving for I_{C1} from (1) & (2)

$$I_{C1} = 1.4 \text{ mA}$$

Substituting in either (1) or (2)

$$V_{C2} = \underline{2.8V}$$

$$\text{and: } V_{E2} = 9 - 100 \times 1.4 \text{ mA} = \underline{8.86V}$$

$$V_{B2} = V_{C1} = 8.86 - 0.7 = \underline{8.16V}$$

For $\beta = 100$ and R open:

In the previous two cases

$$I_{D1} = 0.07 \text{ mA}, I_{E1} = 1.4 \text{ mA}$$

$$\text{if } \beta = 100 \rightarrow I_{B1} \approx 0.014 \text{ mA}$$

which is a significant amount compared to 0.07 mA
 \rightarrow must be taken into account

The bottom two resistors have equal voltage drops thus,
 CONT.

$$2K \times I_{E1} = 40K \times I_{D1}$$

$$\rightarrow I_{D1} = 0.05 \times I_{E1} \quad (3)$$

$$\text{also: } I_{D1} + I_{B1} = \frac{9 - V_{B1}}{80K}$$

$$I_{E1} \left(\frac{1}{\beta+1} + 0.05 \right)$$

$$\text{for } \beta = 100:$$

$$0.06 \times I_{E1} = \frac{9 - V_{B1}}{80K}$$

$$\rightarrow V_{B1} = 9 - 4800 \times I_{E1} \quad (4)$$

$$\text{also: } V_{B1} = 0.7 + I_{E1} \times 2K \quad (5)$$

$$\text{From (4) \& (5) } \begin{cases} V_{B1} = 3.1V // \\ I_{E1} = 1.22mA \end{cases}$$

$$V_{E1} = 1.22m \times 2K \rightarrow V_{E1} = \underline{2.44V}$$

$$I_{C1} = \alpha I_E = 0.99 \times 1.22m$$

$$= 1.2mA$$

Again: voltage drop on top two resistors is equal

$$2K \cdot I_{D2} = 100 \cdot I_{E2}$$

$$I_{D2} = 0.05 I_{E2}$$

$$\text{but } I_{D2} = 1.2m - \frac{I_{E2}}{\beta+1}$$

$$\Rightarrow 1.2mA = \left(0.05 + \frac{1}{\beta+1} \right) I_{E2}$$

$$I_{E2} = 20mA \quad 0.06$$

$$V_{E2} = 9 - 100 \times 20m = \underline{7V}$$

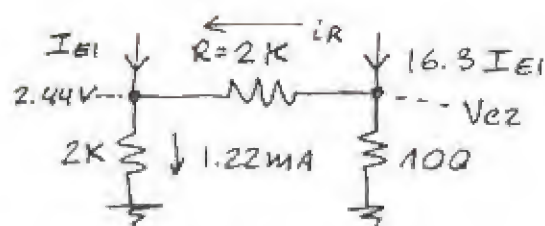
$$V_{B2} = V_{C1} = 7 - 0.7 = \underline{6.3V}$$

$$I_{C1} = \alpha I_{E1} = 19.8mA$$

$$V_{C2} = 100 \times 19.8mA = \underline{1.98V}$$

For $\beta = 100$ and R connected:

To simplify the solution: assume I on R is $\ll I_{E1} \rightarrow V_{E1} = 2.44V$



From top of circuit:

$$I_{E2} = I_{C1} / 0.06$$

$$I_{C2} = \frac{\alpha^2}{0.06} I_{E1}$$

$$I_{C2} = 16.3 \times I_{E1}$$

To obtain I_{E1} :

$$1.22m - I_{E1} = 16.3 I_{E1} - \frac{V_{C2}}{100}$$

$$V_{C2} = 100 (17.2 I_{E1} - 1.22m) \quad (6)$$

also:

$$\frac{V_{C2} - 2.44}{2K} = 1.22m - I_{E1}$$

$$\rightarrow V_{C2} = 2.44 - 2000 I_{E1} + 2.44$$

$$= 4.88 - 2 \times 10^3 \cdot I_{E1} \quad (7)$$

$$\text{From (7) \& (8): } I_{E1} = 1.34mA$$

$$V_{C2} = \underline{2.18V}$$

thus,

$$I_{C1} = 1.33mA$$

$$I_{E2} = 22.1mA$$

$$V_{E2} = 9 - 22.1m \times 100 = 6.79V$$

$$V_{B2} = 6.79 - 0.7 = \underline{6.09V}$$

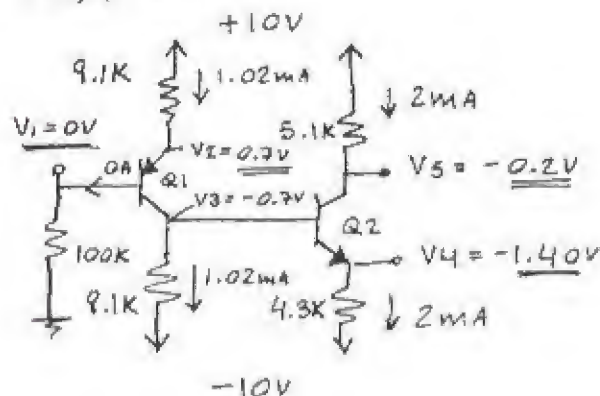
To confirm initial assumption on I of R :

$$\frac{2.44 - 2.18}{2K} = 0.13mA$$

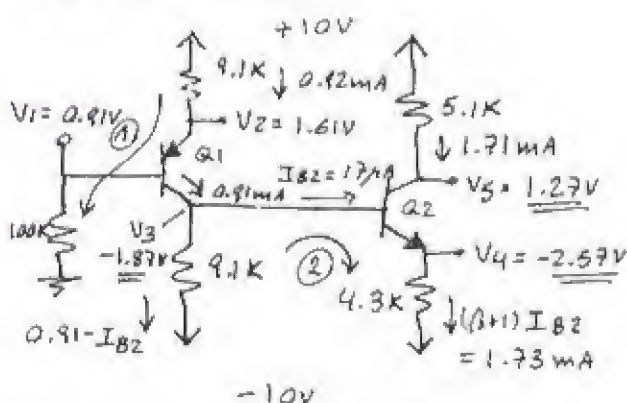
which is 10 times smaller than I_{E1}

5.84

(a) $\beta = \infty$



(b) $\beta = 100$



$$\textcircled{1} 10 - 9.1(\beta + 1)I_{B1} - 0.7 - 100I_{B1} = 0$$

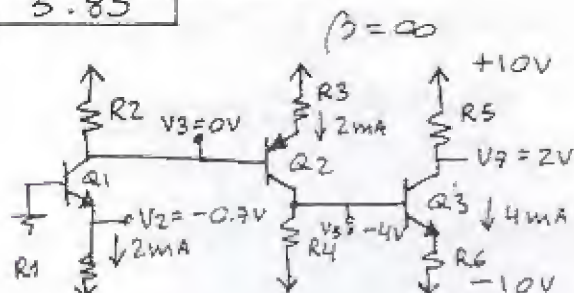
$$\rightarrow I_{B1} = 0.009 \text{ mA}$$

$$\textcircled{2} (0.91 - I_{B2}) \times 9.1 = 0.7 + (\beta + 1)I_{B2} \times 4.3$$

$$\rightarrow I_{B2} = 0.017 \text{ mA}$$

$$\rightarrow I_{E2} = 1.73 \text{ mA}$$

5.85



$$R_1 = \frac{9.3}{2} = 4.7 \text{ k}\Omega$$

$$R_2 = \frac{10}{2} = 5 \rightarrow 5.1 \text{ k}\Omega$$

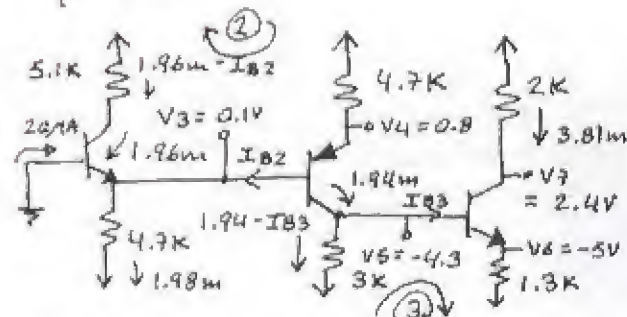
$$R_3 = \frac{9.3}{2} = 4.7 \text{ k}\Omega$$

$$R_4 = \frac{6}{2} = 3 \text{ k}\Omega$$

$$R_5 = \frac{8}{4} = 2 \text{ k}\Omega$$

$$R_6 = \frac{10 - 4.7}{4} = 1.3 \text{ k}\Omega$$

$\beta = 100$



$$\textcircled{2} (1.96 - I_{B2}) \times 5.1 = (\beta + 1)I_{B2} \times 4.7 + 0.7$$

$$I_{B2} = 0.0194 \text{ mA}$$

$$I_{E2} = 1.96 \text{ mA}$$

$$V_3 = 0.1 \text{ V} \quad V_4 = 0.8 \text{ V}$$

$$\textcircled{3} (1.94 - I_{B3}) \times 3 = 0.7 + 1.3 \times (\beta + 1) \cdot I_{B3}$$

$$I_{B3} = 0.038 \text{ mA}$$

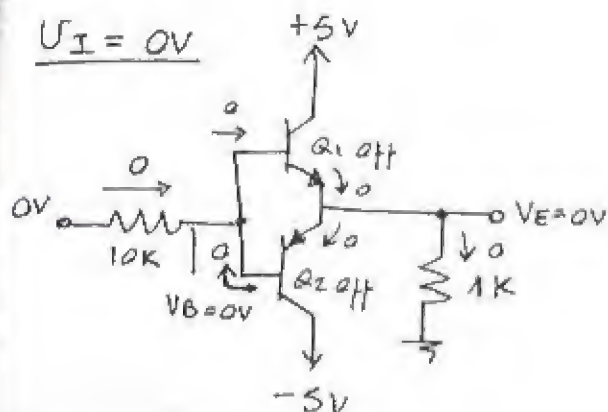
$$I_{E3} = 3.85 \text{ mA}$$

$$V_5 = -4.3 \text{ V} \quad V_6 = -5 \text{ V}$$

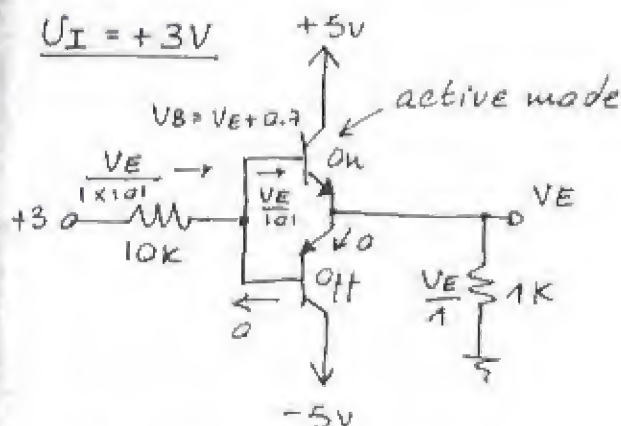
$$V_7 = 2.4 \text{ V}$$

5.86

$U_I = 0V$



$U_I = +3V$

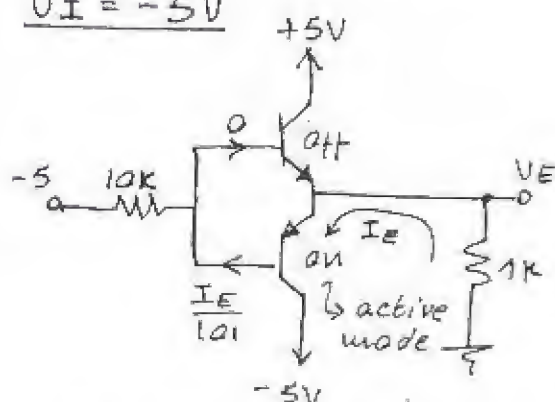


$$3 = \frac{V_E}{101} \times 10 + 0.7 + V_E$$

$$\Rightarrow V_E = 2.08V$$

$$V_B = 2.78V$$

$U_I = -5V$

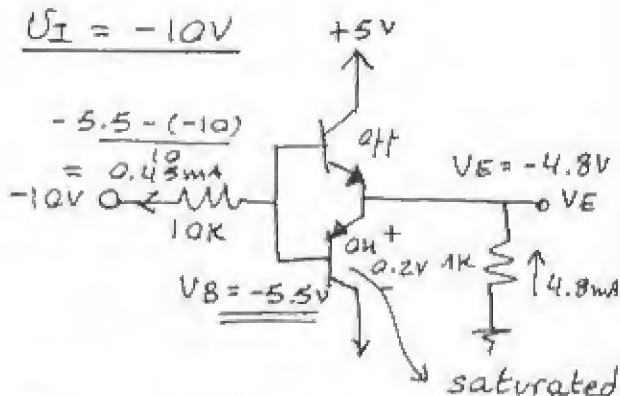


$$I_E = \frac{5 - 0.7}{1 + 10/101} = 3.91mA$$

$$V_E = -3.91V$$

$$V_B = -4.61V$$

$U_I = -10V$

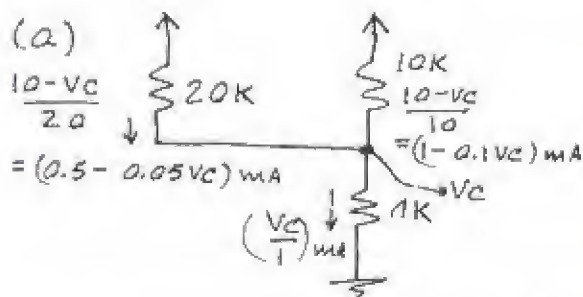


$$\frac{I_C}{I_B} = \frac{4.35}{0.45} = 9.7 < 100$$

thus, Q2 is saturated as assumed

$$V_E = -4.8V \quad V_B = -5.5V$$

5.87



$$(0.5 - 0.005V_C) + (1 - 0.1V_C) = V_C$$

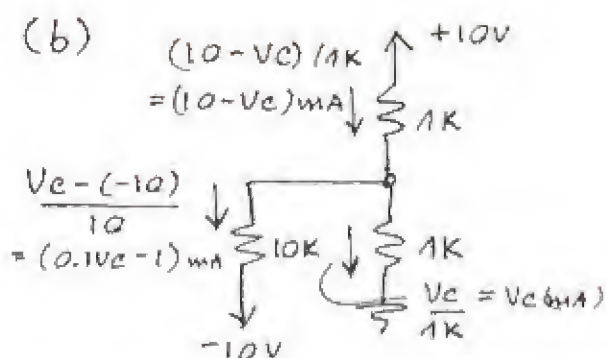
$$V_C = 1.3V$$

$$I_C = \frac{10 - 1.3}{10} = 0.87mA$$

$$I_B = \frac{10 - 1.3}{20} = 0.435mA$$

$$\text{thus } \beta_{\text{forced}} = \frac{0.87}{0.435} = 2$$

CONT.



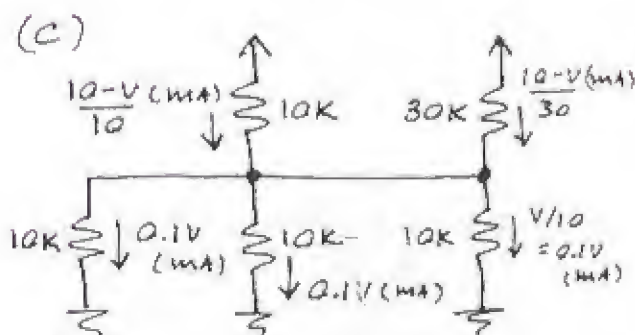
$$10 - V_c = (0.1V_c + 1) + V_c$$

$$\Rightarrow V_c = \underline{\underline{+4.29V}}$$

$$I_c = 4.29 \text{ mA}$$

$$I_B = \frac{4.29 + 10}{10} = 1.43 \text{ mA}$$

$$\beta_{\text{forced}} = \frac{4.29}{1.43} = \underline{\underline{3}}$$



Node equation:

$$\frac{10 - V}{10} + \frac{30 - V}{30} = 0.1V + 0.1V + 0.1V$$

$$30 - 3V + 10 - V = 9V$$

$$40 = 13V$$

$$\Rightarrow V = \underline{\underline{3.08V}}$$

Thus, $V_{c3} \approx V_{c4} \approx 3.08V$

$$I_{B3} = 0.1V = 0.308 \text{ mA}$$

$$I_{E3} = \frac{10 - 3.08}{10} \approx 0.692 \text{ mA}$$

$$I_{c3} = 0.692 - 0.308 = 0.384 \text{ mA}$$

$$\beta_{3 \text{ forced}} = \frac{0.384}{0.308} = \underline{\underline{1.25}}$$

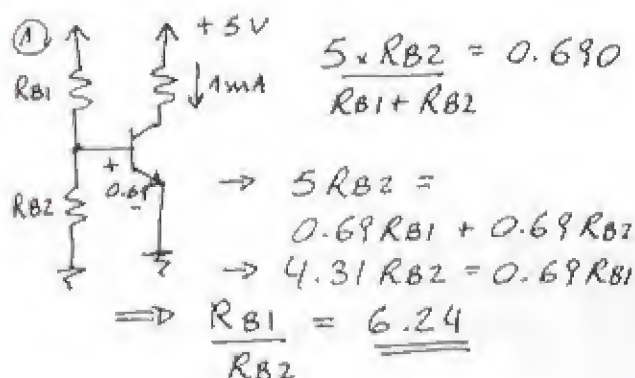
$$I_{c4} = \frac{10 - 3.08}{30} = 0.231 \text{ mA}$$

$$I_{E4} = 0.1V = 0.308 \text{ mA}$$

$$I_{B4} = 0.308 - 0.231 = 0.077 \text{ mA}$$

$$\beta_{4 \text{ forced}} = \frac{0.231}{0.077} = \underline{\underline{3}}$$

5.88



② Since $V_{BE} = \frac{5R_{B2}}{R_{B1} + R_{B2}}$

if both R_{B2} & R_{B1} are at 0.99 or 1.01 of their nominal value $\rightarrow V_{BE}$ will not be affected.

We must consider the cases when one resistor is at 0.99 and the other at 1.01 of their nominal value.

If: $R_{B2}' = 1.01R_{B2}$
 $R_{B1}' = 0.99R_{B1}$

$$\Rightarrow V_{BE} = 0.702V$$

If: $R_{B2}' = 0.99R_{B2}$
 $R_{B1}' = 1.01R_{B1}$

$$\Rightarrow V_{BE} = 0.678V$$

thus V_{BE} ranges from 0.678V to 0.702V

CONT.

For I_C : $I_C = I_S e^{V_{BE}/V_T}$
 for $V_{BE} = 0.690 \rightarrow I_C = 1 \text{ mA}$
 $\Rightarrow I_S = 1.032 \times 10^{-15}$

for $V_{BE} = 0.678 \rightarrow I_C = 0.618 \text{ mA}$
 $V_{BE} = 0.702 \rightarrow I_C = 1.62 \text{ mA}$

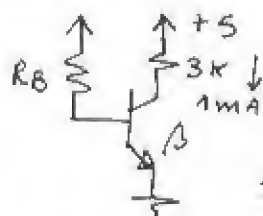
I_C ranges from 0.618 mA to 1.62 mA .

③ If $R_C = 3 \text{ K}\Omega$

$V_{CE} = 5 - 3 \text{ K} \times 0.62 \text{ mA} = 3.14 \text{ V}$
 $V_{CE} = 5 - 3 \text{ K} \times 1.62 \text{ mA} = 0.14 \text{ V}$

This circuit is too sensitive to parameter variations as shown here for a 1% resistor tolerance.

5.89



$R_B = ?$ if $\beta = 100$

$I_B \times \beta = I_C$
 $\frac{5 - 0.7}{R_B} = \frac{1 \text{ mA}}{100}$

$\rightarrow R_B = 430 \text{ K}\Omega$

$V_{CE} = 5 \text{ V} - 3 \text{ K} \times 1 \text{ mA} = 2 \text{ V}$

If $\beta = 50$: $I_C = \frac{5 - 0.7}{430 \text{ K}} \times 50$

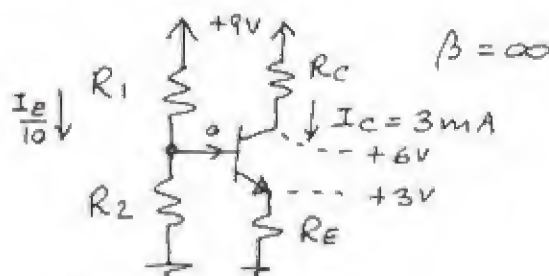
$I_C = 0.50 \text{ mA}$

$\Rightarrow V_{CE} = 5 - 3 \text{ K} \times 0.5 \text{ mA} = +3.5 \text{ V}$

If $\beta = 150$: $I_C = 1.5 \text{ mA}$
 $V_{CE} = 0.5 \text{ V}$

This design is too sensitive to variations of β .

5.90



$R_C = \frac{3 \text{ V}}{3 \text{ mA}} = 1 \text{ K}\Omega$

$R_E = \frac{3 \text{ V}}{3 \text{ mA}} = 1 \text{ K}\Omega$

$V_B = 0.7 + 3 = 3.7 \text{ V}$

$R_1 = \frac{9 - 3.7}{I_E / 10} = 17.7 \text{ K}\Omega$

$9 \text{ V} = (R_1 + R_2) \frac{I_E}{10} \rightarrow R_2 = 12.3 \text{ K}\Omega$

Choose suitable 5% resistors

$R_1 = 17.7 \text{ K} \rightarrow 18 \text{ K}\Omega$

$R_2 = 12.3 \text{ K} \rightarrow 13 \text{ K}\Omega$

$R_1 = R_2 = 1 \text{ K}$

$V_{BB} = \frac{9 \times 13}{18 + 13} = 3.77 \text{ V}$

For these values of R and $\beta = 90$: $R_B = 18 \parallel 13 = 7.55 \text{ K}\Omega$

$I_E = \frac{3.77 - 0.7}{1 \text{ K} + \frac{7.55 \text{ K}}{91}} = 2.83 \text{ mA}$

$\alpha = 0.989 \Rightarrow I_C = 2.80 \text{ mA}$

If R_E is reduced by $\sim \frac{7.55 \text{ K}}{91}$

$\rightarrow R_E = 910 \Omega$

$\Rightarrow I_E = 3.09 \text{ mA}$

$I_C = 3.05 \text{ mA}$

5.91

For $\beta = \infty$ $I_B = 0$, $I_E = 3\text{mA}$

$$R_1 = \frac{9 - 3.7}{I_E/2} = 3.5\text{K}\Omega$$

$$9V = (R_1 + R_2) \frac{I_E}{2} \Rightarrow R_2 = 2.5\text{K}\Omega$$

Suitable 5% resistors:

$$R_1 = 3.5\text{K} \rightarrow 3.3\text{K}\Omega$$

$$R_2 = 2.5\text{K} \rightarrow 2.4\text{K}\Omega$$

$$R_E = R_C = 1\text{K}\Omega$$

$$V_{BB} = \frac{9 \times 2.4}{3.3 + 2.4} = 3.79\text{V}$$

For $\beta = 80$:

$$R_B = (3.3 \parallel 2.4)\text{K} = 1.39\text{K}\Omega$$

$$I_E = \frac{3.79 - 0.7}{1\text{K} + \frac{1.39\text{K}}{81}} = 3.04\text{mA}$$

No need to adjust R_E .

As the current from the voltage divider increases the effect of I_B is reduced.

5.92

$$I_E = \frac{V_{BB} - V_{BE}}{R_E + \frac{R_B}{\beta + 1}}$$

(a) For $\beta = 100$, varying between 50 and 150 the maximum deviation in I_E (from the nominal value obtained for $\beta = 100$) occurs at the low end of β values ($\beta = 50$). Thus, to keep

I_E within $\pm 5\%$ of nominal we must impose the constraint $I_E(\beta = 50) > 0.95 I_E(\beta = 100)$

$$\text{or, } \frac{V_{BB} - V_{BE}}{R_E + \frac{R_B}{51}} \geq 0.95 \frac{V_{BB} - V_{BE}}{R_E + \frac{R_B}{101}}$$

$$\text{or, } R_E + \frac{R_B}{101} \geq 0.95 \left(R_E + \frac{R_B}{51} \right)$$

$$0.05 R_E \geq R_B \left(\frac{0.95}{51} - \frac{1}{101} \right)$$

$$\Rightarrow \frac{R_B}{R_E} \leq 5.73$$

Thus, the largest ratio of R_B/R_E is 5.73

$$(b) I_E \cdot R_E = V_{CC}/3$$

$$\rightarrow \frac{V_{BB} - V_{BE}}{R_E + \frac{R_B}{\beta + 1}} \cdot R_E = \frac{V_{CC}}{3}$$

$$\frac{V_{BB} - 0.7}{1 + \frac{R_B}{R_E} \cdot \frac{1}{\beta + 1}} = \frac{V_{CC}}{3}$$

$$V_{BB} = \frac{1}{3} V_{CC} \left(1 + \frac{5.73}{101} \right) + 0.7$$

$$\Rightarrow \underline{V_{BB} = 0.35 V_{CC} + 0.7}$$

$$(c) V_{CC} = 10\text{V}$$

$$V_{BB} = 0.35 \times 10 + 0.7 = 4.2\text{V}$$

$$\rightarrow \frac{R_2}{R_1 + R_2} \times 10 = 4.2$$

$$\frac{R_2}{R_1 + R_2} = 0.42 \quad (1)$$

$$I_E \cdot R_E = \frac{1}{3} V_{CC}$$

CONT.

$$2 \times R_E = \frac{1}{3} \times 10$$

$$\Rightarrow R_E = \underline{1.67 \text{ K}\Omega}$$

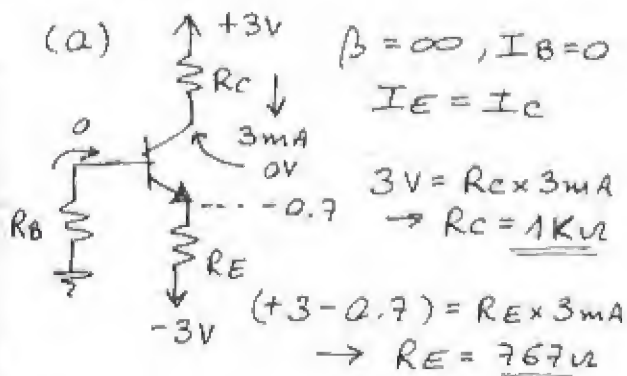
$$R_B = 5.73 \times 1.67 = 9.55 \text{ K}\Omega$$

$$\frac{R_1 \cdot R_2}{R_1 + R_2} = 9.55$$

Substituting from (1) gives

$$R_1 = \frac{9.55}{0.42} = \underline{22.7 \text{ K}\Omega}$$

5.93



(b) $\beta = 90$ $\frac{V_{RE}}{10} = V_{RB}$

$$I_B \cdot R_B = \frac{I_E \cdot R_E}{10}$$

$$\rightarrow \frac{I_E \cdot R_B}{(\beta + 1)} = \frac{I_E \cdot R_E}{10}$$

$$\rightarrow R_B = \frac{(\beta + 1) R_E}{10} \quad (1)$$

also, $0 = V_{RB} + 0.7 + V_{RE} - 3$

$$2.3 = \frac{V_{RE}}{10} + V_{RE}$$

$$\rightarrow V_{RE} = \frac{2.3}{1.1} = 2.09\text{V}$$

$$2.09 = I_E \times R_E \quad (2)$$

but: $I_E = \frac{I_C}{\alpha} = \frac{3\text{mA}}{0.989} = 3.033\text{mA}$

Substituting in (2):

$$R_E = 689\Omega$$

from (1):

$$R_B = \underline{6269\Omega}$$

(c) Standard 5% values:

$$R_C = 1\text{K}\Omega$$

$$R_E = 689\Omega \rightarrow 680\Omega$$

$$R_B = 6269\Omega \rightarrow 6.2\text{K}\Omega$$

(d) $\beta = \infty: I_B = 0$

$$I_C = I_E$$

$$V_B = 0$$

$$V_E = -0.7$$

$$I_E = \frac{3 - 0.7}{R_E} = \frac{3 - 0.7}{680} = \underline{3.38\text{mA}}$$

$$V_C = 3 - 3.38\text{mA} \times 1\text{K} = \underline{-0.38\text{V}}$$

For $\beta = 90$:

$$I_E = \frac{2.3}{\frac{680 + 6.2\text{K}}{91}} = \underline{3.07\text{mA}}$$

$$I_C = \alpha I_E = \underline{3.04\text{mA}}$$

$$V_B = \frac{R_B \cdot I_E}{\beta + 1} = -0.209$$

$$V_E = -0.209 - 0.7 = \underline{0.909\text{V}}$$

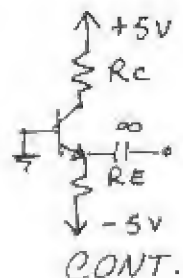
$$V_C = 3 - I_C \cdot R_C = 3 - 3.04 \times 1 = \underline{-0.04\text{V}}$$

5.94

$$V_E = -0.7\text{V}$$

To obtain $I_E = 1\text{mA}$

$$R_E = \frac{-0.7 - (-5)}{1} = 4.3\text{K}\Omega$$



CONT.

To maximize gain while allowing $\pm 1V$ signal at collector, design for a dc collector voltage of $+1V$.

Thus,

$$R_C = \frac{5-1}{I_C} \approx \frac{4}{1} = \underline{\underline{4\text{ k}\Omega}} \quad (\alpha \approx 1)$$

For 100°C rise in temperature, V_{BE} decreases by $2 \times 100 = 200\text{mV}$ and thus I_E increases by $\frac{0.2V}{R_E}$

$$= \frac{0.2V}{4.3\text{ k}\Omega} = 0.047\text{ mA}$$

i.e. an increase of 4.7%

The change in β from 50 to 150 causes α to change from 0.980 to 0.993 which implies an increase in collector current of 1.3%. Thus the overall increase in I_C is 6%

5.95

To allow a collector voltage swing of $\pm 1V$, we design for:

$$V_C = V_B + 1 \\ = 0.7 + 1 = 1.7V$$

$$I_E = 0.5\text{ mA}$$

$$\rightarrow R_C = \frac{5-1.7}{0.5} = \underline{\underline{6.6\text{ k}\Omega}}$$

For $\beta = 100$:

$$I_B = \frac{I_E}{\beta+1} = \frac{0.5}{101} \approx 5\mu\text{A}$$

$$I_B \cdot R_B = 1V$$

$$R_B = \frac{1V}{5\mu\text{A}} = \frac{1}{5}\text{ M}\Omega = \underline{\underline{200\text{ k}\Omega}}$$

Now, if the BJT used has $\beta = 50$, the emitter current resulting can be found from Eq (5.74)

$$I_E = \frac{V_{CC} - V_{BE}}{R_C + \frac{R_B}{\beta+1}}$$

$$= \frac{5 - 0.7}{6.6 + \frac{200}{51}} = \underline{\underline{0.41\text{ mA}}}$$

$$\text{and } I_B = \frac{0.41}{51} \approx 8\mu\text{A}$$

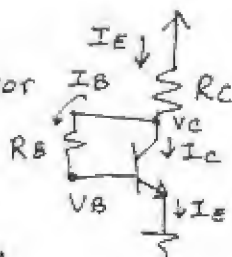
Thus the collector will be higher than the base by $8 \times 0.2 = 1.6V$, allowing for a $\pm 1.6V$ signal swing at the collector.

For $\beta = 150$:

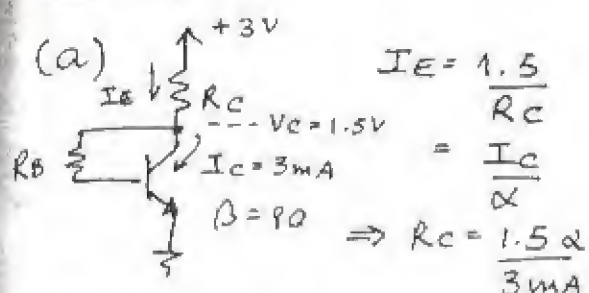
$$I_E = \frac{5 - 0.7}{6.6 + \frac{200}{151}} = 0.54\text{ mA}$$

$$I_B = \frac{0.54}{151} \approx 36\mu\text{A}$$

Thus the collector voltage will be higher than that of the base by $3.6 \times 0.2 \approx 0.72V$ allowing for only $\pm 0.72V$ signal swing.



5.96



$$R_C = 495\Omega$$

$$1.5 = R_B I_B + 0.7$$

$$R_B = \frac{1.5 - 0.7}{I_C / \beta} = 24\text{K}\Omega$$

(b) Standard 5% values

$$R_B = 24\text{K}\Omega$$

$$R_C = 495\Omega \rightarrow 510\Omega$$

$$\text{then, } I_E = \frac{3 - 0.7}{510 + 24\text{K}} = 2.97\text{mA}$$

$$I_C = I_E \cdot \alpha = 2.93\text{mA}$$

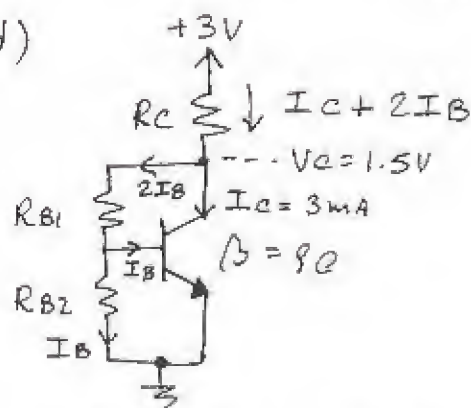
$$V_C = 3 - 2.97\text{mA} \times 510 = 1.48\text{V}$$

(c) $\beta = \infty$ $I_B = 0$, $V_B = 0.7\text{V}$

$$I_C = I_E = \frac{3 - 0.7}{510} = 4.5\text{mA}$$

$$V_C = 3 - 4.5\text{mA} \times 510 = 0.7\text{V}$$

(d)



$$I_B = \frac{I_C}{\beta} = \frac{3\text{mA}}{90} = 0.033\text{mA}$$

$$1.5\text{V} = 2I_B \times R_{B1} + 0.7$$

$$\rightarrow R_{B1} = 12.1\text{K}\Omega$$

$$0.7 = I_B \times R_{B2}$$

$$\rightarrow R_{B2} = 21.2\text{K}\Omega$$

on R_C :

$$I_C + 2I_B = 3.066\text{mA}$$

$$R_C = \frac{1.5\text{V}}{3.066\text{mA}} = 489\Omega$$

Standard 5% values:

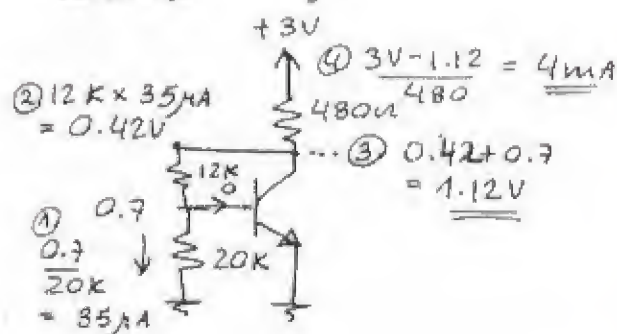
$$R_{B1} = 12.1\text{K} \rightarrow 12\text{K}\Omega$$

$$R_{B2} = 21.2\text{K} \rightarrow 20\text{K}\Omega$$

$$R_C = 489.2 \rightarrow 480\Omega$$

Re-evaluate if $\beta = \infty$:

$$I_B = 0$$



5.97

$$I_B = I_C / \beta = 3\text{mA} / 90 = 0.033\text{mA}$$

$$V_C = R_B \cdot I_B + 0.7$$

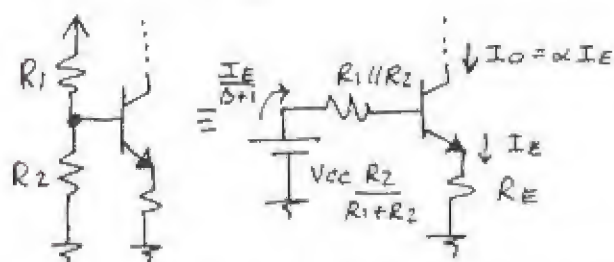
$$V_C = 1.5\text{V} \rightarrow R_B = 24.2\text{K}\Omega$$

$$I_E = \frac{I_C}{\alpha} = 3.03\text{mA}$$

$$I = I_C - I_B = I_E$$

$$I = 3.03\text{mA}$$

5.98



$$V_{CC} \cdot \frac{R_2}{R_1 + R_2} = \frac{I_E}{\beta + 1} (R_1 \parallel R_2) + V_{BE} + I_E R_E$$

$$\Rightarrow I_E = \frac{V_{CC} \frac{R_2}{R_1 + R_2} - V_{BE}}{R_E + \frac{R_1 \parallel R_2}{\beta + 1}}$$

Thus,

$$I_O = \alpha I_E = \alpha \cdot \left(\frac{V_{CC} \frac{R_2}{R_1 + R_2} - V_{BE}}{R_E + \frac{R_1 \parallel R_2}{\beta + 1}} \right)$$

Q.E.D.

5.99

For $\beta = \infty$:

$$R_{E2} = \frac{2}{0.1} = 20 \text{ k}\Omega$$

$$R_C = \frac{5 - 0.8}{0.1} = 42 \text{ k}\Omega$$

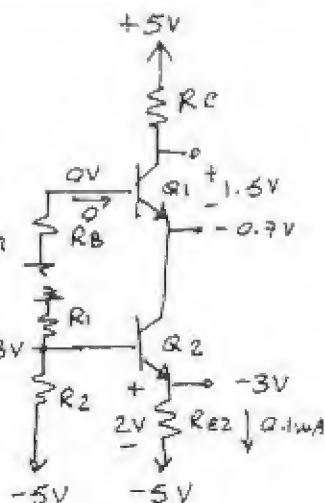
$$\text{Select } R_C = 43 \text{ k}\Omega$$

$$\text{Also } V_{R1} = 2.3 \text{ V}$$

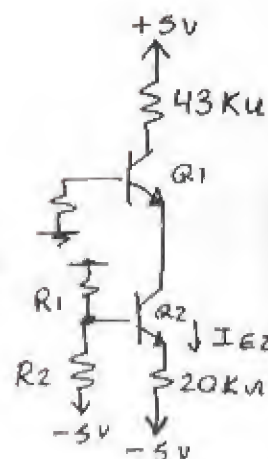
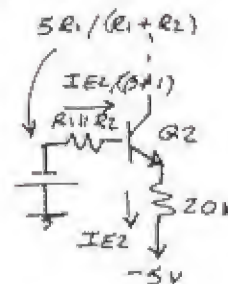
$$V_{R2} = 2.7 \text{ V}$$

$$\Rightarrow \frac{R_1}{R_2} = \frac{2.3}{2.7}$$

$$\Rightarrow R_1 = \frac{23}{27} \cdot R_2$$



For $\beta = 50$



$$I_{E2} = \frac{-5 \cdot \frac{R_1}{R_1 + R_2} - 0.7 + 5}{\frac{20 + \frac{R_1 \parallel R_2}{\beta + 1}}{\beta + 1}}$$

$$= \frac{5 \cdot \frac{R_1}{R_1 + R_2} - 0.7}{\frac{20 + \frac{1}{51} \cdot \frac{R_1 R_2}{R_1 + R_2}}{\beta + 1}}$$

$$\text{Substitute } R_1 = \frac{23}{27} R_2$$

$$I_{E2} = \frac{5}{1 + 23/27} - 0.7$$

$$= \frac{2}{20 \left[1 + \frac{1}{20 \times 51} \times \frac{23 R_2}{50} \right]}$$

$$V_{RE2} = I_{E2} \times 20 = \frac{2}{1 + \frac{0.46}{51} \cdot R_2}$$

For a reduction less than 5%

$$\frac{2}{1 + \frac{0.46 R_2}{51 \times 20}} \geq 0.95 \times 2$$

$$R_2 \leq \left(\frac{1}{0.95} - 1 \right) \frac{51 \times 20}{0.46} = 116.7 \text{ k}\Omega$$

CONT.

Select $R_2 = 120 \text{ k}\Omega$

$$R_1 = \frac{23}{27} R_2 = 102.2 \text{ k}\Omega$$

Select $R_1 = 100 \text{ k}\Omega$

For these values,

$$\beta = \infty: I_{E2} = \frac{-5 \times \frac{100}{220} - 0.7 + 5}{20} = \frac{2.027}{20} = 0.101 \text{ mA}$$

$$V_{RE2} = 2.027 \text{ V}$$

$$\beta = 50: I_{E2} = \frac{2.027}{20 + \frac{120 \times 100}{220 \times 51}}$$

$$I_{E2} = 0.096 \text{ mA}$$

$$I_{C2} = 0.98 \times 0.096 = 0.094 \text{ mA}$$

$$I_{C1} = 0.98 \times 0.094 = 0.092 \text{ mA}$$

To determine R_B :

$$V_{B1} = -I_{B1} \cdot R_B = -\frac{I_{C1}}{\beta} \cdot R_B = -\frac{0.094}{50} \cdot R_B$$

$$V_{E1} = V_{B1} - 0.7 = -\frac{0.094}{50} \cdot R_B - 0.7$$

$$V_{C1} = 5 - R_C I_{C1} = 5 - 43 \times 0.092 = 1.044 \text{ V}$$

$$V_{CE1} = 1.044 + \frac{0.094}{50} \cdot R_B + 0.7 = 2.5 \text{ V}$$

$$\Rightarrow R_B = 402 \text{ k}\Omega$$

Select $R_B = 390 \text{ k}\Omega$

Now,

$$\text{For } \beta = 50: I_{C1} = 0.092 \text{ mA}$$

$$V_{B1} = -\frac{0.092 \times 390}{50} = -0.717 \text{ V}$$

$$V_{E1} = -1.417 \text{ V}$$

$$V_{CE1} = 1.044 + 1.417 = 2.46 \approx 2.5 \text{ V}$$

For $\beta = 100$:

$$I_{E2} = \frac{2.027}{\frac{R_1 R_2}{R_1 + R_2} \cdot \frac{1}{101} + 20} = 0.099 \text{ mA}$$

$$I_{C1} = 0.099 \times 0.99 \times 0.99 = 0.097 \text{ mA}$$

$$V_{C1} = 0.829 \text{ V}$$

$$V_{B1} = -0.378 \text{ V}$$

$$V_{E1} = -1.078 \text{ V}$$

$$V_{CE1} = 1.91 \text{ V}$$

For $\beta = 200$:

$$I_{E2} = \frac{2.027}{\frac{R_1 R_2}{R_1 + R_2} \cdot \frac{1}{201} + 20} = 0.1 \text{ mA}$$

$$I_{C1} = 0.1 \times 0.995 \times 0.995 = 0.099 \text{ mA}$$

$$V_{C1} = 0.743 \text{ V}$$

$$V_{B1} = -0.193 \text{ V}$$

$$V_{E1} = -0.893 \text{ V}$$

$$V_{CE1} = 1.636 \approx 1.64 \text{ V}$$

5.100

Refer to Fig P5.100

Assuming $\beta = \infty \rightarrow I_{B3} = 0$

$$V_{B3} = \frac{V_{CC} - V_{BE1} - V_{BE2}}{R_1 + R_2} \times R_2 \dots + V_{BE1} + V_{BE2}$$

$$V_{E3} = V_{B3} - V_{BE3}$$

$$I_O = \frac{\alpha V_{E3}}{R_E}$$

$$I_O = \frac{\alpha}{R_E} \left[\frac{(V_{CC} - V_{BE1} - V_{BE2}) R_2 + V_{BE1} + V_{BE2}}{R_1 + R_2} - V_{BE3} \right]$$

CONT.

Now, if the circuit is designed so that all three transistors conduct equal currents, then $V_{BE1} = V_{BE2} = V_{BE3} = V_{BE}$

and I_0 becomes:

$$I_0 = \frac{\alpha}{R_E} \left[\frac{(V_{CC} - 2V_{BE})R_2 + V_{BE}}{R_1 + R_2} \right]$$

To eliminate the V_{BE} terms in this equation we select $R_1 = R_2$, resulting in

$$I_0 = \frac{\alpha V_{CC}}{2R_E} \quad \text{Q.E.D.}$$

Now, to make the current through Q_1 and Q_2 equal to that through Q_3 (which is I_0/α)

$$\frac{V_{CC} - 2V_{BE}}{2R_1} = \frac{V_{CC}}{2R_E}$$

$$\Rightarrow R_1 = R_2 = R_E \left(1 - \frac{2V_{BE}}{V_{CC}} \right)$$

$$\text{For } V_{CC} = 10V, \alpha = 1 \\ I_0 = 0.5mA$$

$$0.5 = \frac{10}{2R_E} \Rightarrow R_E = \underline{\underline{10K\Omega}}$$

$$R_1 = R_2 = 10 \left(1 - \frac{2 \times 0.7}{10} \right) \\ = \underline{\underline{8.6K\Omega}}$$

$$V_{C3|_{min}} = I_0 \cdot R_E + V_{BE} \\ = 0.5 \times 10 + 0.7 \\ = \underline{\underline{5.7V}}$$

5.101

Refer to Fig. P5.101

$$I_0 = 2mA = \alpha \times \frac{5 - 0.7}{R} \approx \frac{4.3}{R}$$

$$\Rightarrow R = \underline{\underline{2.15K\Omega}}$$

$$V_{C|_{min}} = 0V \quad (\text{In actual practice, } V_{C|_{min}} \approx 0.4V)$$

5.102

(a) Using the exponential characteristic:

$$I_C = I_C e^{V_{BE}/V_T}$$

thus,

$$I_C = I_C e^{V_{BE}/V_T} - I_C$$

$$\text{giving } \frac{I_C}{I_C} = e^{V_{BE}/V_T} - 1$$

(b) Using small-signal approximation:

$$i_c = g_m v_{be} = \frac{I_C}{V_T} \cdot v_{be}$$

$$\text{Thus, } \frac{i_c}{I_C} = \frac{v_{be}}{V_T}$$

See table below

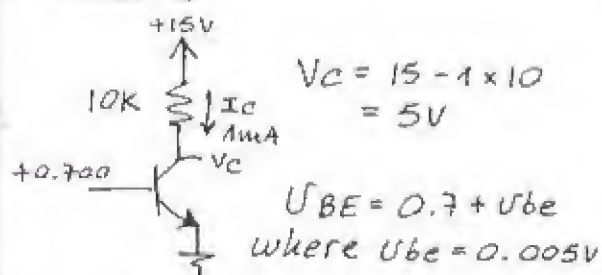
For signals of $\pm 5mV$, the error introduced by the small-signal approximation is 10%.

The error increases to above 20% for signals of $\pm 10mV$.

CONT.

V_{be} (mV)	i_c/I_c Expan.	i_c/I_c small-signal	% Error
+1	+0.041	+0.040	-2
-1	-0.039	-0.040	+2
+2	+0.083	+0.080	-4
-2	-0.077	-0.080	+4
+5	+0.221	+0.200	-9.5
-5	-0.181	-0.200	+10.3
+8	+0.377	+0.320	-15.2
-8	-0.274	-0.320	+16.8
+10	+0.492	+0.400	-18.7
-10	-0.330	-0.400	+21.3
+12	+0.616	+0.480	-22.1
-12	-0.381	-0.480	+25.9

5.103



$$i_c \approx I_c \left(1 + \frac{V_{be}}{V_T}\right) \text{ Eq. (5.83)}$$

$$i_c \approx I_c + i_c \quad \text{where:}$$

$$i_c = \frac{1m \times 0.005}{25m} = 0.2m$$

$$i_c = 1mA + 0.2mA$$

$$V_c = V_{cc} - i_c R_c \quad \text{Eq. (5.101)}$$

$$\Rightarrow V_c = \underbrace{i_c R_c}_{0.2m \times 10K}$$

$$V_c = 5V - 2V$$

$$\text{gain} = \frac{-2V}{0.005V} = -400V/V$$

$$\text{while } -g_m R_c = \frac{-1m}{25m} \cdot 10K = -400 \frac{V}{V}$$

5.104

$$g_m = \frac{I_c}{V_T} = \frac{1.2mA}{25mV} = 48 \frac{mA}{V}$$

$$r_\pi = \frac{\beta}{g_m} = \frac{120}{48 \times 10^{-3}} = 2.5K\Omega$$

$$r_e = \frac{r_\pi}{\beta + 1} = \frac{2500}{121} = 20.6\Omega$$

For a bias current of 120 μA
i.e. 10 times lower:

$$g_m = \frac{48}{10} = 4.8mA/V$$

$$r_\pi = 10 \times 2.5 = 25K\Omega$$

$$r_e = 10 \times 20.6 = 206\Omega$$

5.105

$$I_c = 2mA \Rightarrow g_m = \frac{2mA}{25mV}$$

$$g_m = 80mA/V$$

$$r_e = \frac{V_T}{I_E}, \quad I_E = I_c \frac{(\beta + 1)}{\beta}$$

$$I_E = 2mA \times \frac{51}{50} = 2.04mA$$

$$r_e = \frac{25m}{2.04m} = 12.25\Omega$$

$$r_\pi = \frac{\beta}{g_m} = \frac{50}{80 \times 10^{-3}} = 625\Omega$$

$$\text{gain} : -g_m R_c$$

For $R_c = 5K\Omega$ and $\hat{V}_{be} = 5mV$

$$\hat{V}_o = -80m \times 5K \times 5mV$$

$$= -2V$$

5.106

$$g_m = \frac{50 \text{ mA}}{V} = \frac{I_C}{V_T}$$

$$\Rightarrow I_C = g_m \times V_T = 50 \text{ mA} \times 25 \text{ mV} = 1.25 \text{ mA}$$

$$r_{\pi} = 2 \text{ K} = \frac{\beta}{g_m} \Rightarrow \beta = 2 \text{ K} \times 50 \text{ mA}$$

$$\beta = \frac{100}{g_m} \rightarrow \alpha = \frac{100}{101} = 0.99$$

$$I_E = \frac{I_C}{\alpha} = \frac{1.25 \text{ mA}}{0.99} = 1.26 \text{ mA}$$

$$\begin{aligned} i_C(t) &= I_C + g_m v_{be}(t) \\ &= 1 \text{ mA} + 40 \cdot 10^3 \times 0.005 \sin \omega t \\ &= 1 + 0.2 \sin \omega t, \text{ mA} \end{aligned}$$

$$\begin{aligned} v_C(t) &= 5 - R_C i_C(t) \\ &= 2 - 0.6 \sin \omega t, \text{ V} \end{aligned}$$

$$\begin{aligned} i_B(t) &= i_C(t) / \beta \\ &= \frac{1 + 0.2 \sin \omega t}{100}, \text{ mA} \\ &= 10 + 2 \sin \omega t, \mu\text{A} \end{aligned}$$

$$\text{Voltage gain} = \frac{-0.6}{0.005} = -120 \text{ V/V}$$

5.107

$$g_m \text{ varies from: } 1.2 \times 60 = 72 \frac{\text{mA}}{\text{V}} \text{ to } 0.8 \times 60 = 48 \frac{\text{mA}}{\text{V}}$$

$$\beta \text{ varies from } 50 \text{ to } 200$$

$$r_{in|base} = r_{\pi} = \beta / g_m$$

$$\begin{aligned} \text{Largest value: } r_{\pi} &= \frac{\beta_{\max}}{g_{m\min}} = \frac{200}{48 \text{ mA/V}} \\ &= 4.2 \text{ K}\Omega \end{aligned}$$

$$\begin{aligned} \text{Smallest value: } r_{\pi} &= \frac{\beta_{\min}}{g_{m\max}} = \frac{50}{72 \text{ mA/V}} \\ &= 694 \Omega \end{aligned}$$

5.108

Refer to Fig. 5.48.

$$V_C = 2 \text{ V} \Rightarrow I_C = \frac{V_{CC} - V_C}{R_C}$$

$$I_C = \frac{5 - 2}{3 \text{ K}} = 1 \text{ mA}$$

$$g_m = \frac{I_C}{V_T} = \frac{1 \text{ mA}}{25 \text{ mV}} = 40 \frac{\text{mA}}{\text{V}}$$

5.109

$$i_C = I_C + g_m \hat{v}_{be} \sin \omega t$$

$$V_C = V_{CC} - I_C R_C - g_m \hat{v}_{be} R_C \sin \omega t$$

To maintain BJT in active region, $V_C > V_{BE}$, thus $V_{CC} - I_C R_C - g_m R_C \hat{v}_{be} > V_{BE} + \hat{v}_{be}$.

To obtain the largest possible output signal we design such that this constraint is satisfied with the equality sign, that is:

$$V_{CC} - R_C I_C - g_m R_C \hat{v}_{be} = V_{BE} + \hat{v}_{be}$$

$$\begin{aligned} \text{substituting } g_m &= \frac{I_C}{V_T} \text{ gives:} \\ V_{CC} - R_C I_C - R_C I_C \frac{\hat{v}_{be}}{V_T} &= V_{BE} + \hat{v}_{be} \\ \Rightarrow R_C I_C (1 + \frac{\hat{v}_{be}}{V_T}) &= V_{CC} - V_{BE} - \hat{v}_{be} \end{aligned}$$

CONT.

$$R_C I_C = \frac{(V_{CC} - V_{BE} - \hat{V}_{be})}{(1 + \frac{\hat{V}_{be}}{V_T})} \quad \text{Q.E.D.}$$

$$\text{Voltage gain} = -g_m \cdot R_C$$

$$= -\frac{I_C}{V_T} \cdot R_C$$

$$= -\frac{V_{CC} - V_{BE} - \hat{V}_{be}}{V_T + \hat{V}_{be}}$$

For $V_{CC} = 5V$, $V_{BE} = 0.7V$ and $\hat{V}_{be} = 5mV$

$$R_C I_C = \frac{5 - 0.7 - 0.005}{1 + \frac{0.005}{0.025}} = 3.6V$$

Thus,

$$V_C = 5 - 3.6 = +1.4V$$

Amplitude of output signal is

$$= 1.4 - (V_{BE} + \hat{V}_{be})$$

$$= 1.4 - 0.7 - 0.005$$

$$= 0.695V$$

$$\text{Voltage gain} = -\frac{0.695}{0.005} = -139 \frac{V}{V}$$

Check

$$\text{Voltage gain} = -\frac{(5 - 0.7 - 0.005)}{0.025 + 0.005}$$

$$= -143 \frac{V}{V}$$

The difference is caused by decimal rounding-up at $R_C I_C$.

Otherwise:

$$\text{Voltage gain} = -\frac{0.716}{0.005}$$

$$= -143 \frac{V}{V}$$

5.110

	a	b	c	d	e	f	g
α	1.000	0.990	0.98	1	0.990	0.90	0.991
β	∞	100	50	∞	100	9	16
$I_C (mA)$	1.00	0.99	1.00	1.00	0.248	4.5	17.5
$I_E (mA)$	1.00	1.00	1.02	1.00	0.25	5	18.6
$I_B (mA)$	0	0.010	0.020	0	0.002	0.5	1.10
$g_m (\frac{mA}{V})$	40	39.6	40	40	0.01	180	700
$r_e (\Omega)$	25	25	24.5	25	100	5	1.34
$r_{\pi} (\Omega)$	∞	25K	1.25K	∞	10.1K	50	22.7

5.111

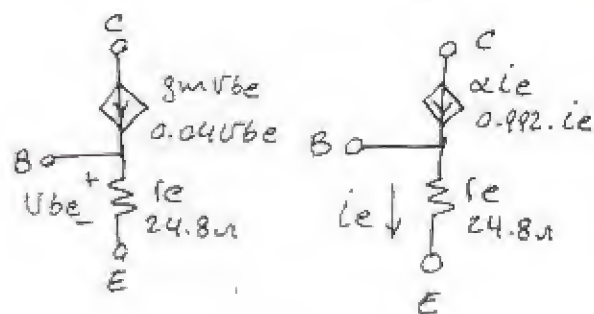
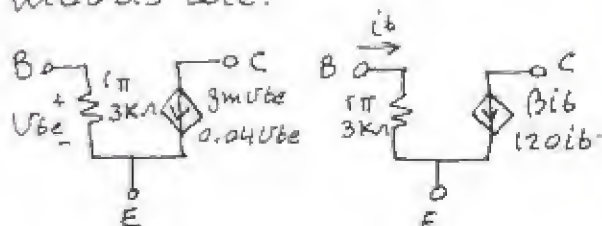
$$I_C = 1mA, \beta = 120, \alpha = 0.992$$

$$g_m = \frac{I_C}{V_T} = \frac{1}{25} = 40 \frac{mA}{V}$$

$$r_{\pi} = \frac{\beta}{g_m} = \frac{120}{40 \times 10^{-3}} = 3K\Omega$$

$$r_e = \frac{V_T}{I_E} = \frac{\alpha}{g_m} = \frac{0.992}{40 \times 10^{-3}} = 24.8\Omega$$

The four equivalent circuit models are:



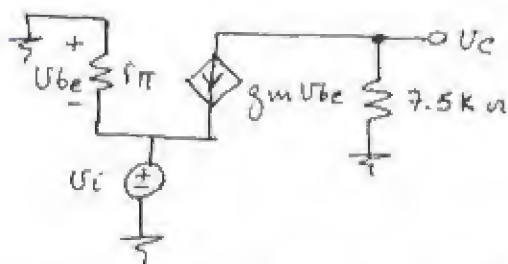
5.112

Refer to Fig P5.112
 β very high $\rightarrow \alpha = 1$

$$I_C = I_E = 0.5 \text{ mA}$$

$$V_C = 5 - 7.5 \times 0.5 = +1.25 \text{ V}$$

$$g_m = \frac{I_C}{V_T} = \frac{0.5 \text{ mA}}{25 \text{ mV}} = 20 \frac{\text{mA}}{\text{V}}$$



Observe that $U_{be} = -U_i$
 the output voltage U_c is found from:

$$U_c = -g_m U_{be} \times 7.5 \text{ K}$$

Thus the voltage gain is

$$\frac{U_c}{U_i} = g_m \times 7.5 \text{ K} = 20 \times 7.5 = \underline{\underline{150 \text{ V/V}}}$$

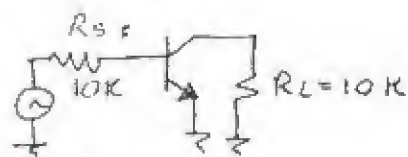
5.113

$$\frac{U_c}{U_{be}} = -g_m R_c \Rightarrow U_{be} = \frac{1}{50 \times 2} = 10 \text{ mV p-p}$$

$$I_b = \frac{U_{be}}{r_{\pi}} = \frac{10 \times 10^{-3}}{\beta / g_m} = \frac{0.01}{100 / 0.05}$$

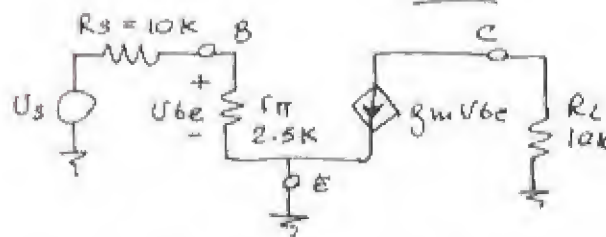
$$I_b = \underline{\underline{0.005 \text{ mA p-p}}}$$

5.114



$$g_m = 40 \frac{\text{mA}}{\text{V}}, \quad r_{\pi} = 2.5 \text{ K}$$

$$r_{\pi} = \beta / g_m \Rightarrow \beta = 2.5 \text{ K} \times 40 \frac{\text{mA}}{\text{V}} = \underline{\underline{100}}$$



$$U_{be} = U_s \cdot \frac{r_{\pi}}{R_s + r_{\pi}} = 0.2 \times U_s$$

$$U_c = -g_m U_{be} \cdot R_L = -g_m (0.2 U_s) \cdot R_L$$

$$U_c = -80 U_s$$

$$\Rightarrow \text{gain } \frac{U_c}{U_s} = \underline{\underline{-80}}$$

To double the gain:

If I_C is fixed $\rightarrow g_m$ does not change.

$$\rightarrow \frac{U_{be}}{U_s} = 0.4 \quad (2 \times 0.2)$$

$$\rightarrow \frac{r_{\pi}}{R_s + r_{\pi}} = 0.4 \quad \wedge \quad R_s = 10 \text{ K}$$

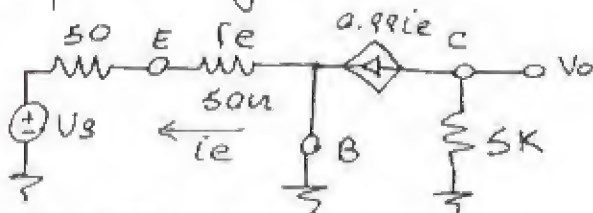
$$\Rightarrow r_{\pi} = 6.6 \text{ K}$$

$$\text{Since } r_{\pi} = \frac{\beta}{g_m} \Rightarrow \beta = 6.6 \text{ K} \times 40 \frac{\text{mA}}{\text{V}}$$

$$\beta = \underline{\underline{264}}$$

5.115

Refer to Fig. P5.115



$$i_e = \frac{V_T}{I_E} = \frac{25\text{mV}}{0.5\text{mA}} = 50\mu$$

$$R_{in} = R_s + r_e = 100\Omega$$

$$V_o = -0.99 i_e \times 5K$$

$$\text{but: } i_e = \frac{-V_s}{R_{in}} = \frac{-V_s}{100}$$

$$\Rightarrow V_o = +0.99 \times 5K \cdot \frac{V_s}{100}$$

$$\frac{V_o}{V_s} = 49.5 \text{ V/V}$$

5.116

Refer to Fig P5.116

$$\beta = 200 \rightarrow \alpha = 0.995$$

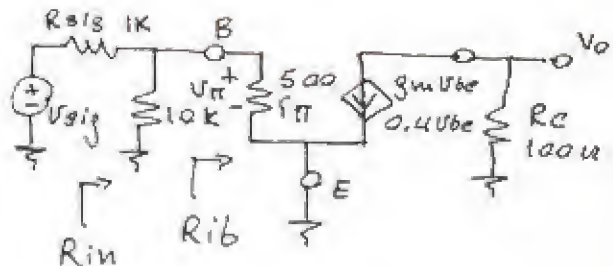
$$I_c = \alpha I_E = 0.995 \times 10\text{mA} = 9.95\text{mA}$$

$$V_c = 9.95\text{mA} \times 100 = 0.995\text{V}$$

$$I_B = \frac{10\text{mA}}{200} = 0.05\text{mA}$$

$$V_B = 1.5 - 10K \times 0.05\text{mA} = 1\text{V}$$

$$\Rightarrow V_{BE} = +0.005 \rightarrow \text{Active region.}$$



$$g_m = \frac{I_c}{V_T} = \frac{9.95\text{mA}}{25\text{mV}} = 0.4 \text{ A/V}$$

$$r_\pi = \frac{\beta}{g_m} = \frac{200}{0.4} = 500\Omega$$

$$R_{ib} = r_\pi = 500\Omega$$

$$R_{in} = 10K \parallel r_\pi = 476\Omega$$

$$V_{be} = V_{sig} \times \frac{R_{in}}{R_{sig} + R_{in}} = V_{sig} \times 0.32$$

also:

$$\begin{aligned} V_o &= -g_m V_{be} \cdot R_c \\ &= -g_m R_c \times 0.32 V_{sig} \\ &= -0.4 \times 100 \times 0.32 V_{sig} \\ &= -12.8 V_{sig} \end{aligned}$$

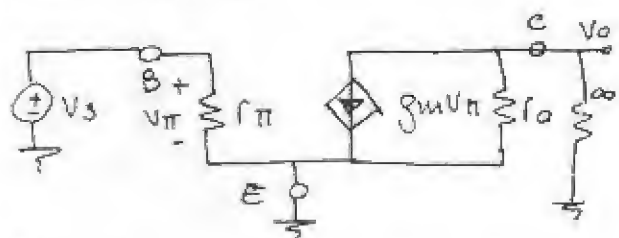
$$\Rightarrow \text{gain } \frac{V_o}{V_s} = -12.8 \approx -13 \text{ V/V}$$

$$\text{If } V_o = \pm 0.4\text{V:}$$

$$\hat{V}_s = \frac{\hat{V}_o}{13} = 30\text{mV}$$

$$\hat{V}_{be} = 0.32 \times 30\text{mV} = 9.6\text{mV}$$

5.117



$$V_s = V_{be} \Rightarrow \frac{V_o}{V_s} = -g_m \times r_o$$

CONT.

$$\text{but: } r_o = \frac{V_A}{I_c} = \frac{V_A}{V_T \cdot g_m}$$

$$\Rightarrow \frac{V_o}{V_s} = \frac{-V_A}{V_T}$$

$$\text{if } V_A = 25V \Rightarrow \frac{V_o}{V_s} = -1000 \frac{V}{V}$$

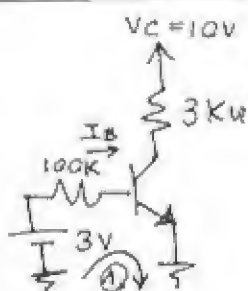
$$\text{if } V_A = 250V \Rightarrow \frac{V_o}{V_s} = -10,000 \frac{V}{V}$$

5.118

DC Analysis:

$$\textcircled{1} I_B = \frac{3 - 0.7}{100}$$

$$I_B = 0.023 \text{ mA}$$



Saturation begins to occur when $V_c \leq 0.7V$

$$\therefore I_c \geq \frac{10 - 0.7}{3} = 3.1 \text{ mA}$$

$$I_c = \beta I_B \rightarrow \beta \geq \frac{3.1}{0.023} = 135$$

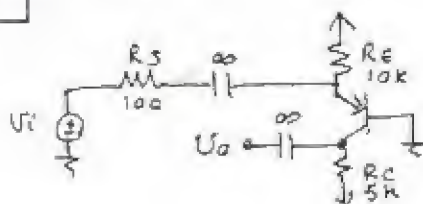
$\beta = 25$:

$$r_e = \frac{V_T}{I_E} = \frac{V_T}{(\beta + 1) I_B} = \frac{25 \times 10^{-3}}{26 \times 0.023 \times 10^{-3}}$$

$$r_e = 41.8 \Omega$$

$$g_m = \frac{\alpha}{r_e} = \frac{25/26}{41.8} = 23 \frac{\text{mA}}{\text{V}}$$

5.119



$$\frac{V_o}{V_i} = \alpha \frac{r_e \parallel R_E}{R_E \parallel r_e + R_s} \cdot \frac{1}{r_e} \cdot R_c$$

$$= 0.99 \frac{(27 \parallel 100)}{(27 \parallel 100) + 100} \times \frac{1}{27} \times 5 \times 10^3$$

$$= 38.9 \approx 39 \text{ V/V}$$

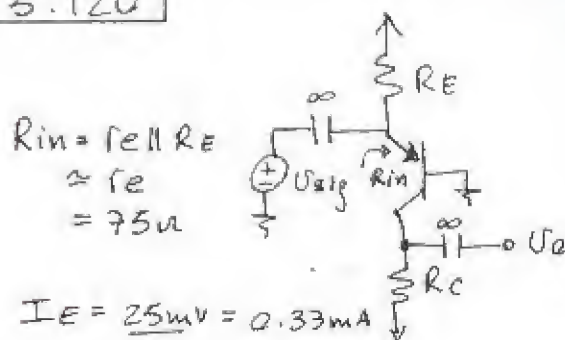
The amplifier clips when the peak output signal exceeds the difference between $V_c (-5.4V)$ and the negative supply $(-10V)$; see Fig. 5.56.

That is when the peak output signal is $4.6V$

This corresponds to a peak input signal of

$$\hat{V}_i = \frac{4.6}{39} = 118 \text{ mV}$$

5.120



$$R_{in} = r_e \parallel R_E$$

$$\approx r_e$$

$$= 75 \Omega$$

$$I_E = \frac{25 \text{ mV}}{75 \Omega} = 0.33 \text{ mA}$$

$$R_E = \frac{10 - 0.7}{0.33} = 28 \text{ k}\Omega$$

$$n = 2.8$$

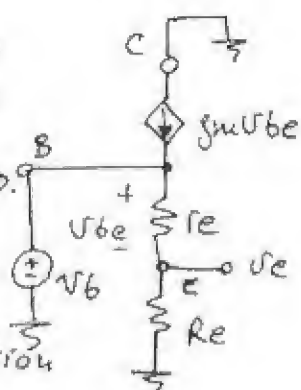
$$R_c = 14 \text{ k}\Omega$$

$$\frac{V_o}{V_i} = \alpha \frac{R_c}{r_e} = \frac{14}{0.075} = 187 \text{ V/V}$$

5.121

(a) Using the voltage divider rule:

$$\frac{V_e}{V_b} = \frac{R_e}{R_e + r_e} \quad \text{Q.E.D.}$$



(b) Node equation at B:

$$\begin{aligned} i_b &= \frac{V_{be}}{r_e} - g_m V_{be} \\ &= \frac{V_{be}}{r_e} (1 - g_m r_e) \\ &= \frac{V_{be}}{r_e} (1 - g_m \frac{\alpha}{g_m}) \\ &= \frac{V_{be}}{r_e} (1 - \alpha) \\ &= \frac{V_{be}}{r_e} (1 - \frac{\beta}{\beta + 1}) \\ &= \frac{V_{be}}{r_e} \cdot \frac{1}{(\beta + 1)} \end{aligned}$$

But, from voltage-divider rule

$$V_{be} = V_b \cdot \frac{r_e}{r_e + R_e}$$

$$\Rightarrow i_b = \frac{1}{(\beta + 1) r_e} \cdot \frac{V_b \cdot r_e}{r_e + R_e}$$

from which we find

$$R_{in} = \frac{V_b}{i_b} = (\beta + 1)(R_e + r_e)$$

Q.E.D.

For $R_e = 1 \text{ k}\Omega$, $\beta = 100$ and $I_E = 1 \text{ mA}$

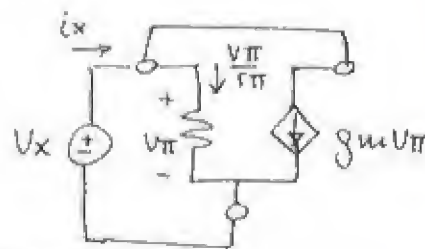
$$r_e = \frac{V_T}{I_E} = \frac{25 \text{ mV}}{1 \text{ mA}} = 25 \Omega$$

Thus,

$$\frac{V_e}{V_b} = \frac{1000}{1000 + 25} = 0.976 \text{ V/V}$$

$$\begin{aligned} R_{in} &= (100 + 1)(1000 + 25) \Omega \\ &= 101 \times 1.025 \text{ k}\Omega \\ &= 103.5 \text{ k}\Omega \end{aligned}$$

5.122



$$\begin{aligned} i_x &= \frac{V_{\pi}}{r_{\pi}} + g_m V_{\pi} \\ &= \frac{V_{\pi}}{r_{\pi}} (1 + g_m r_{\pi}) \\ &= \frac{V_{\pi}}{r_{\pi}} (1 + \beta) \end{aligned}$$

But $V_{\pi} = V_x$

$$\Rightarrow R_{in} = \frac{V_x}{i_x} = \frac{V_{\pi}}{i_x} = \frac{r_{\pi}}{\beta + 1}$$

$$R_{in} = \underline{\underline{r_e}}$$

5.123

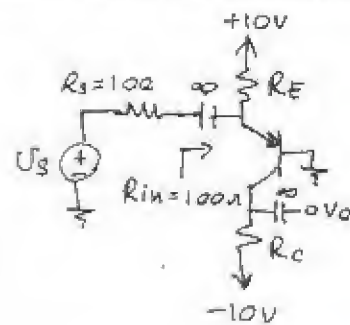
$$R_{in} = R_E \parallel r_e \quad r_e \approx 100 \Omega$$

$$\text{Thus, } \frac{V_T}{I_E} = 100 \rightarrow I_E = 0.25 \text{ mA}$$

$$V_E = 0.7 \text{ V}$$

$$R_E = \frac{10 - 0.7}{1 \text{ mA}}$$

$$= 9.3 \text{ k}\Omega$$



CONT.

Selection of a value for R_c :

The voltage gain is directly proportional to R_c ,

$$\begin{aligned}\frac{V_o}{V_s} &= \frac{V_e}{V_s} \cdot \frac{V_o}{V_e} \\ &= \frac{R_{in}}{R_s + R_{in}} \cdot \frac{\alpha R_c}{r_e} \\ &\approx \frac{100}{100 + 100} \cdot \frac{R_c}{0.1} \\ &= 5R_c, R_c \text{ in } k\Omega.\end{aligned}$$

For an emitter-base signal as large as 10mV, the signal at the collector will be $g_m R_c \times 0.010$ volts. Thus the maximum collector voltage in the positive direction will be:

$$\begin{aligned}V_{c|max} &= V_c + 0.01 g_m R_c \\ &= -10 + I_c R_c + 0.01 \times \frac{1}{0.1} \times R_c \\ &= -10 + 0.25 R_c + 0.1 R_c \\ &= -10 + 0.35 R_c\end{aligned}$$

To prevent saturation, $V_{c|max} \leq V_B$ which is 0V.

Thus to obtain maximum gain while allowing an emitter-base signal as large as 10mV and at the same time keeping the transistor in the active mode we select R_c from:

$$\begin{aligned}-10 + 0.35 R_c &= 0 \\ \Rightarrow R_c &= \underline{\underline{28.6 k\Omega}}\end{aligned}$$

$$\text{Voltage gain} = \frac{V_o}{V_s} = 5R_c = 143 V/V$$

5.124

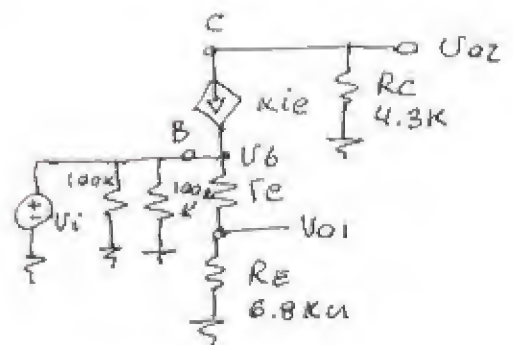
Refer to Fig P5.124
For large β , the DC base current will be ~ 0
Thus the DC voltage at the base can be found directly using the voltage divider rule

$$V_B = 15 \cdot \frac{100}{100 + 100} = 7.5V$$

$$\text{if: } V_{BE} = 0.7$$

$$V_E = 7.5 - 0.7 = 6.8V$$

$$\rightarrow I_E = \frac{6.8V}{6.8 k\Omega} = \underline{\underline{1mA}}$$



$$V_B = V_i$$

$$\rightarrow \frac{V_{o1}}{V_i} = \frac{R_E}{R_E + r_e} \quad \text{Q.E.D.}$$

Also,

$$i_e = \frac{V_B}{r_e + R_E} = \frac{V_i}{r_e + R_E}$$

and,

$$\begin{aligned}V_{o2} &= -\alpha i_e R_c \\ &= -\frac{\alpha R_c V_i}{r_e + R_E}\end{aligned}$$

Thus,

$$\frac{V_{o2}}{V_i} = -\frac{\alpha R_c}{R_E + r_e} \quad \text{Q.E.D.}$$

CONT.

Substituting $r_e = \frac{V_T}{I_E} = 25 \Omega$

and $R_E = 6.8 k\Omega$, $R_C = 4.3 k\Omega$
and $\alpha \approx 1$ gives

$$\frac{V_{o1}}{V_i} = \frac{6.8}{0.025 + 6.8} = \underline{\underline{0.996 \text{ V/V}}}$$

$$\frac{V_{o2}}{V_i} = \frac{-4.3}{6.8 + 0.025} = \underline{\underline{0.63 \text{ V/V}}}$$

If the node labeled V_{o2} is connected to ground:
 $R_E = 0$

$$\frac{V_{o2}}{V_i} = -\frac{\alpha R_C}{r_e}$$

5.125

If: $R_i = 10 k\Omega$, $A_{vo} = 100 \text{ V/V}$
 $R_o = 100 \Omega$, $R_{sig} = 2 k\Omega$ and
 $R_{in} = 8 k\Omega$ when $R_L = 1 k\Omega$
then:

$$G_m = \frac{A_{vo}}{R_o} = \frac{100}{100} = \underline{\underline{1 \text{ A/V}}}$$

$$A_v = A_{vo} \cdot \frac{R_L}{R_L + R_o} = 100 \times \frac{1k}{1k + 100} = \underline{\underline{91 \text{ V/V}}}$$

$$G_{vo} = \frac{R_i}{R_i + R_{sig}} \cdot A_{vo} = \frac{10k}{10k + 2k} \times 100 = \underline{\underline{83.3 \text{ V/V}}}$$

$$G_v = \frac{R_{in}}{R_{in} + R_{sig}} \times A_{vo} \times \frac{R_L}{R_L + R_o}$$

$$= \frac{8k}{8k + 2k} \times 100 \times \frac{1k}{1k + 100} = \underline{\underline{72.7 \text{ V/V}}}$$

$$R_{out} = \frac{G_{vo}}{G_v} \cdot R_L - R_L = \frac{8.3 \times 1k - 1k}{72.7}$$

$$= \underline{\underline{146 \Omega}}$$

$$A_i = \frac{V_o / R_L}{V_i / R_{in}} = A_v \cdot \frac{R_{in}}{R_L} = 91 \times \frac{8k}{1k}$$

$$= \underline{\underline{728 \text{ A/A}}}$$

5.126

Refer to Fig. P5.126

$$R_i = 900 k\Omega$$

$$A_{vo} = 10 \text{ V/V}$$

$$R_o = 1.43 k\Omega$$

$$R_{in} = 400 k\Omega \text{ when } R_L = 10 k\Omega$$

$$(a) i_i \equiv V_i / R_{in}$$

$$\Rightarrow \frac{V_i}{R_{in}} = \frac{V_i}{R_i} - f \cdot i_o$$

$$\text{where } i_o = \frac{A_{vo} V_i}{R_o + R_L}$$

$$\rightarrow \frac{V_i}{R_{in}} = \frac{V_i}{R_i} - f \cdot \frac{A_{vo} V_i}{R_o + R_L}$$

Solving for f :

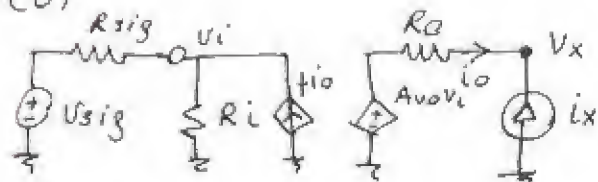
$$f = \left(\frac{1}{R_i} - \frac{1}{R_{in}} \right) \cdot \frac{R_o + R_L}{A_{vo}}$$

Thus,

$$f = \left(\frac{1}{900k} - \frac{1}{400k} \right) \cdot \frac{(1.43k + 10k)}{10}$$

$$f = \underline{\underline{-1.6 \times 10^{-3}}}$$

(b)



$$R_{out} = \frac{V_x}{i_x} \Big|_{V_{sig}=0}$$

If $V_{sig}=0$: on the left hand side

$$V_i = f \cdot i_o (R_{sig} \parallel R_i)$$

$$V_i = (-1.6 \times 10^{-3} \times (100k \parallel 900k)) i_o$$

$$= -144 i_o$$

On the right hand side:

$$V_x = R_o i_x + A_{vo} V_i$$

$$= R_o i_x + A_{vo} (-144 i_o)$$

$$= R_o i_x + A_{vo} (+144) i_x$$

CONT.

$$\rightarrow V_x = i_x (R_o + A_{vo} \times 144)$$

$$R_{out} = \frac{V_x}{i_x} = 1.43K + 10 \times 144$$

$$R_{out} = \underline{\underline{2.87K\Omega}}$$

Which is the same value as in Example 5.17

5.127

$$G_v = \frac{R_{in}}{R_{in} + R_{sig}} \cdot A_{vo} \cdot \frac{R_L}{R_L + R_o} = G_{vo} \cdot \frac{R_L}{R_L + R_{out}}$$

$$\text{but } G_{vo} = \frac{R_i}{R_i + R_{sig}} \cdot A_{vo}$$

Substituting G_{vo} :

$$\frac{R_{in}}{R_{in} + R_{sig}} \cdot A_{vo} \cdot \frac{R_L}{R_L + R_o} = \frac{R_i}{R_i + R_{sig}} \cdot A_{vo} \cdot \frac{R_L}{R_L + R_{out}}$$

$$\rightarrow \frac{R_{in}}{R_i} \cdot \frac{(R_{sig} + R_i)}{(R_{sig} + R_{in})} = \frac{R_L + R_o}{R_L + R_{out}} \quad \text{Q.E.D.}$$

$$(a) \text{ for } R_L = \infty$$

$$\frac{R_{in}}{R_i} \cdot \frac{(R_{sig} + R_i)}{(R_{sig} + R_{in})} = 1$$

$$R_{in} R_{sig} + R_{in} R_i = R_i R_{sig} + R_i R_{in}$$

$$R_{in} \cdot R_{sig} = R_i \cdot R_{sig}$$

$$\rightarrow R_{in} = R_i$$

Q.E.D.

(b) for $R_{sig} = 0$

$$\frac{R_{in}}{R_i} \cdot \frac{R_i}{R_{in}} = \frac{R_L + R_o}{R_L + R_{out}}$$

$$\rightarrow R_{out} = R_o$$

Q.E.D.

(c) For $R_{sig} = \infty$

$$\frac{R_{in}}{R_i} = \frac{R_L + R_o}{R_L + R_{out}}$$

$$R_{out} = (R_L + R_o) \frac{R_i}{R_{in}} - R_L //$$

In Example 5.17:

$$R_{out} = (10K + 1.43K) \frac{900}{400} - 10$$

$$= \underline{\underline{15.7K\Omega}}$$

5.128

Refer to Fig. 5.60(a)

$$I_C = 0.2mA \Rightarrow I_E = \frac{I_C}{\alpha}$$

$$I_E = \frac{0.2}{\beta} \cdot (\beta + 1) = 0.202mA$$

$$r_e = \frac{V_T}{I_E} = \frac{0.025}{0.202mA} = 123.76\Omega$$

$$R_i = (\beta + 1) r_e = \underline{\underline{12.5K\Omega}}$$

$$\frac{V_o}{V_s} = -g_m (R_{eff}) \cdot \frac{R_i}{R_i + R_s}$$

$$\approx -\frac{\alpha}{r_e} \cdot R_c \cdot \frac{R_i}{R_i + R_s}$$

$$= -\frac{100}{101} \times \frac{24K}{123.76} \times \frac{12.5K}{12.5K + 10K}$$

$$\frac{V_o}{V_s} = -\underline{\underline{106.7V/V}}$$

$$R_o = R_{eff} \approx R_c = \underline{\underline{24K\Omega}}$$

$$\frac{V_o}{V_s} = \frac{V_o}{V_s} \Big|_{\text{no load}} \times \frac{10}{10 + 24}$$

$$= -106.7 \times \frac{10}{34} = -\underline{\underline{31.4V/V}}$$

5.129

$$I_C = 0.2 \text{ mA} \Rightarrow r_e = 123.76 \Omega$$

$$R_i = (\beta + 1)(r_e + R_E)$$

$$= (101)(123.76 + 125) = \underline{25.1 \text{ K}\Omega}$$

$$\frac{V_o}{V_s} = \frac{-\alpha R_C \times R_i}{r_e + R_E R_i + R_s}$$

$$= \frac{-100 \times 24 \text{ K} \times 25.1 \text{ K}}{101(123.76 + 125) 25.1 \text{ K} + 10 \text{ K}}$$

$$= \underline{-68.30 \text{ V/V}}$$

$$R_o = R_C = \underline{24 \text{ K}\Omega}$$

With $10 \text{ K}\Omega$ load

$$\frac{V_o}{V_s} = -68.30 \times \frac{10}{10 + 24} = \underline{-20 \text{ V}}$$

Without R_E $V_{\pi} \leq 5 \text{ mV}$

$$V_{\pi} = \frac{(\beta + 1) r_e}{(\beta + 1) r_e + R_s} \cdot V_s$$

$$= \frac{(101)(123.76)}{(101)(123.76) + (10 \text{ K})} \cdot V_s \leq 5 \text{ mV}$$

$$\Rightarrow V_s \leq \underline{9 \text{ mV}}$$

With R_E

$$V_{\pi} = \frac{(\beta + 1) r_e}{(\beta + 1)(r_e + R_E) + R_s} \cdot V_s \leq 5 \text{ mV}$$

$$V_s \leq 5 \text{ mV} \left[\frac{(101)(123.76 + 125) + 10 \text{ K}}{101 \times 123.76} \right]$$

$$V_s \leq \underline{14 \text{ mV}}$$

5.130

Refer to Fig. P5.130

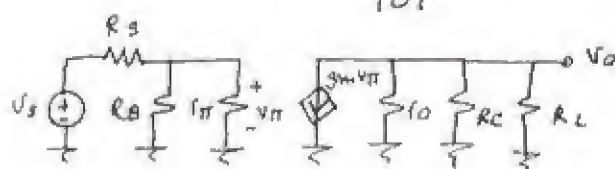
$$I_E = \frac{V_{BB} - V_{BE}}{R_E + R_B / (\beta + 1)}$$

where, $V_{BB} = V_{CC} \cdot \frac{R_2}{R_1 + R_2}$

$$= 9 \cdot \frac{15}{27 + 15} = 3.21 \text{ V}$$

$$R_B = R_1 \parallel R_2 = 15 \parallel 27 = 9.64 \text{ K}\Omega$$

Thus, $I_E = \frac{3.21 - 0.7}{1.2 + \frac{9.64}{101}} = \underline{1.94 \text{ mA}}$



$$g_m = \frac{I_C}{V_T} = \frac{0.99 \times 1.94}{0.025} = 76.8 \frac{\text{mA}}{\text{V}}$$

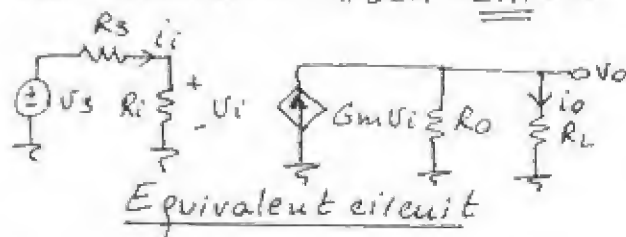
$$r_{\pi} = \frac{\beta}{g_m} = \frac{100}{76.8} = 1.3 \text{ K}\Omega$$

$$r_o = \frac{V_A}{I_C} = \frac{100}{0.99 \times 1.94} = 52.1 \text{ K}\Omega$$

$$R_i = R_B \parallel r_{\pi} = 9.64 \parallel 1.3 = \underline{1.15 \text{ K}\Omega}$$

$$G_m = -g_m = -\underline{76.8 \frac{\text{mA}}{\text{V}}}$$

$$R_o = R_C \parallel r_o = 2.2 \parallel 52.1 = \underline{2.11 \text{ K}\Omega}$$



$$A_V = \frac{V_o}{V_s} = \frac{V_i'}{V_s} \cdot \frac{V_o}{V_i'}$$

$$= \frac{R_i}{R_s + R_i} \cdot \frac{G_m (R_o \parallel R_L) V_i'}{V_i'}$$

$$= \frac{-1.15}{10 + 1.15} \times 76.8 \times (2.11 \parallel 2)$$

$$= \underline{-8.13 \text{ V/V}}$$

$$A_i = \frac{i_o}{i_i} = \frac{V_o \cdot R_L}{V_s / (R_s + R_i)}$$

CONT.

$$\begin{aligned} \rightarrow A_i &= \frac{V_o}{V_s} \cdot \frac{R_s + R_i}{R_L} \\ &= -8.13 \times \frac{(10 + 1.15)}{2} \\ &= \underline{\underline{-45.3 \text{ A/A}}} \end{aligned}$$

5.131

Refer to Fig. P5.130.
 $V_{CC} = 9V$ $V_{BB} = \frac{1}{3} V_{CC} = 3V$

Neglecting the base current,
 $R_1 + R_2 = \frac{9}{0.2} = 45 \text{ k}\Omega$

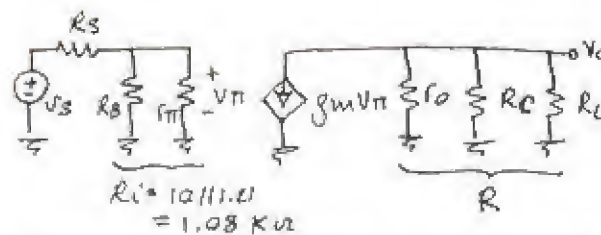
$$\begin{aligned} \frac{R_2}{R_1 + R_2} &= \frac{1}{3} \\ \Rightarrow R_2 &= 15 \text{ k}\Omega, R_1 = 30 \text{ k}\Omega \\ R_B &= R_1 \parallel R_2 = \frac{30 \times 15}{45} = 10 \text{ k}\Omega \end{aligned}$$

$$\begin{aligned} I_E &= \frac{V_{BB} - V_{BE}}{R_E + \frac{R_B}{\beta + 1}} \\ 2 &= \frac{3 - 0.7}{R_E + 10/101} \Rightarrow R_E = 1.05 \text{ k}\Omega \end{aligned}$$

Use $R_E = 1 \text{ k}\Omega$

The resulting I_E will be

$$\begin{aligned} I_E &= \frac{3 - 0.7}{1 + 10/101} = 2.09 \text{ mA} \\ I_C &= \alpha I_E = 0.99 \times 2.09 = 2.07 \text{ mA} \\ g_m &= \frac{I_C}{V_T} = \frac{2.07}{0.025} = 82.9 \frac{\text{mA}}{\text{V}} \\ r_{\pi} &= \frac{\beta}{g_m} = \frac{100}{82.9} = 1.21 \text{ k}\Omega \\ f_o &= \frac{V_A}{I_C} = \frac{100}{2.07} = 48.3 \text{ k}\Omega. \end{aligned}$$



$$\begin{aligned} \frac{V_o}{V_s} &= \frac{V_{\pi}}{V_s} \cdot \frac{V_o}{V_{\pi}} = \frac{R_i}{R_s + R_i} \cdot \frac{-g_m V_{\pi} R}{V_{\pi}} \\ &= \frac{-1.08}{10 + 1.08} \times 82.9 \times R \end{aligned}$$

To obtain $\frac{V_o}{V_s} = -8 \frac{\text{V}}{\text{V}}$ we use:

$$R = \frac{8 \times 11.08}{1.08 \times 82.9} = 0.99 \text{ k}\Omega$$

$$\begin{aligned} \text{Now } R &= r_o \parallel R_C \parallel R_L \\ 0.99 &= 48.3 \parallel R_C \parallel 2 \\ \Rightarrow R_C &= 2.04 \text{ k}\Omega \end{aligned}$$

Use $R_C = 2 \text{ k}\Omega$

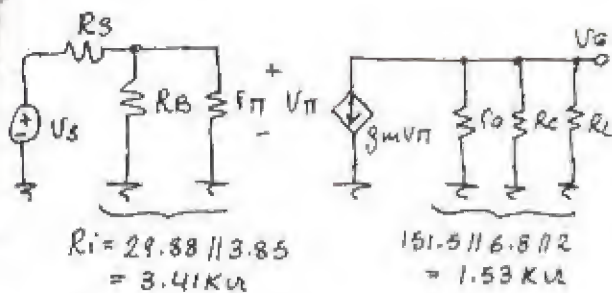
Check: $V_C = 9 - 2.07 \times 2 = 4.86 \text{ V}$
 while $V_B \approx 3 \text{ V}$. Thus in active mode as assumed.

5.132

Refer to Fig. P5.130

$$\begin{aligned} V_{BB} &= 9 \cdot \frac{47}{82 + 47} = 3.28 \text{ V} \\ R_B &= 47 \parallel 82 = 29.88 \text{ k}\Omega \\ I_E &= \frac{3.28 - 0.7}{3.6 + \frac{29.88}{101}} = 0.66 \text{ mA} \\ I_C &= 0.99 \times 0.66 = 0.65 \text{ mA} \\ g_m &= \frac{0.65}{0.025} = 26 \frac{\text{mA}}{\text{V}} \\ r_{\pi} &= \frac{100}{26} = 3.85 \text{ k}\Omega \\ f_o &= \frac{100}{0.66} = 151.5 \text{ k}\Omega \end{aligned}$$

CONT.



$$A_v = \frac{V_o}{V_S} = \frac{3.41}{10 + 3.41} \times -26 \times 1.53$$

$$= -10.1 \text{ V/V} \quad \text{Which is about 25\%}$$

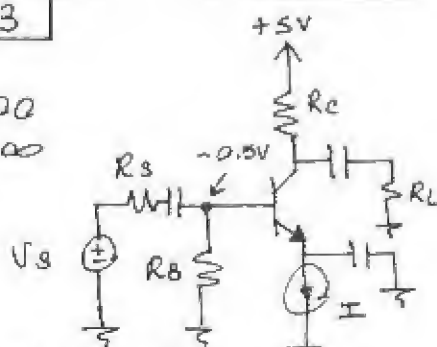
higher than in the original design. The improvement is not as large as might have been expected because although R_i increases, g_m decreases by about the same factor.

Indeed most of the improvement is due to the increase in R_c and hence in the effective load resistance.

5.133

$$\beta = 100$$

$$I_0 = \infty$$



$$R_{in} = 5 \text{ K}\Omega, \quad R_{in} = R_B \parallel r_{\pi}$$

$$\Rightarrow 5 \text{ K} = \frac{R_B \cdot r_{\pi}}{R_B + r_{\pi}}$$

$$5 \text{ K} (r_{\pi} + R_B) = R_B r_{\pi}$$

$$\text{but } r_{\pi} = \frac{V_T}{I_B} \text{ and } R_B \cdot I_B = 0.5$$

$$\Rightarrow 5 \text{ K} \cdot \frac{V_T}{I_B} = 0.5 (r_{\pi} + 5 \text{ K})$$

$$\text{thus, } r_{\pi} = 5250 \Omega$$

$$\text{then } R_B = 105 \text{ K}$$

$$\text{choose } R_B = \underline{100 \text{ K}\Omega}$$

$$\text{and } I_B = 4.76 \mu\text{A}$$

$$I_E = (\beta + 1) I_B = 101 \times 4.76 \mu\text{A}$$

$$I_E = 0.48 \text{ mA}$$

$$I = I_E \rightarrow I \approx \underline{0.5 \text{ mA}}$$

To avoid saturation:

$$V_C - V_B \geq -0.5$$

$$V_C = 5 \text{ V} - R_C [I_C + g_m V_{be}]$$

$$I_C = I \cdot \alpha = 0.5 \text{ mA} \times 100/101$$

$$= 0.49 \text{ mA}$$

$$g_m = \frac{V_T}{V_{be}} = \frac{25 \text{ mV}}{0.49 \text{ mA}} \approx 50 \frac{\text{mA}}{\text{V}}$$

$$V_{be} = 0.005 \text{ V}$$

$$\rightarrow V_C = 5 - R_C [0.49 \text{ mA} + 50 \text{ mA/V} \times 5 \text{ mV}]$$

$$= 5 - 0.74 \times 10^{-3} \times R_C$$

Then:

$$V_C - V_B = (5 - 0.74 \text{ mA} R_C) - (-0.5 + V_{be})$$

$$= 5.495 - 0.74 \text{ mA} R_C \geq -0.5$$

$$R_C \leq \underline{8.1 \text{ K}\Omega}$$

Base-to-Collector open circuit

gain:

$$\frac{V_C}{V_B} = -g_m R_C = -50 \text{ mA/V} \times 8.1 \text{ K}$$

$$= -405 \text{ V/V}$$

For $R_S = 10 \text{ K}$, $R_L = 10 \text{ K}$

$$\frac{V_a}{V_b} = -g_m (R_C \parallel R_L)$$

$$= -50 \text{ mA/V} \times 4.47 \text{ K}$$

$$= -223 \text{ V/V}$$

$$\frac{V_C}{V_S} = \frac{V_b}{V_S} \cdot \frac{V_a}{V_b} = \frac{5}{5 + 10} \times -223$$

$$= \underline{-74.3 \text{ V/V}}$$

5.134

Refer to Fig P5.134

$$I_E = 0.5 \text{ mA}$$

$$(a) \quad I_E = \frac{15 - 0.7}{R_E + R_S \frac{\beta + 1}{\beta}}$$

$$0.5 = \frac{14.3}{R_E + \frac{2.5}{100}}$$

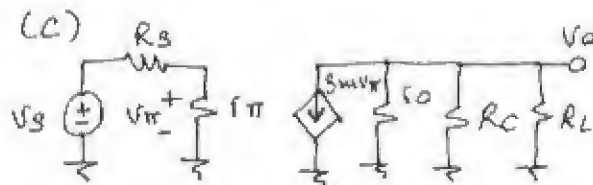
$$\Rightarrow R_E = \underline{28.57 \text{ K}\Omega}$$

$$(b) \quad V_C = 15 - R_C \cdot I_C$$

$$5 = 15 - R_C \times 0.99 \times 0.5 \text{ mA}$$

$$\Rightarrow R_C = \underline{20.2 \text{ K}\Omega}$$

$$\approx \underline{20 \text{ K}\Omega}$$



$$R_L = 10 \text{ K}\Omega, R_S = 2.5 \text{ K}\Omega$$

$$r_o = 200 \text{ K}\Omega$$

$$g_m = \frac{I_C}{V_T} \approx \frac{0.5 \text{ mA}}{25 \text{ mV}} = 20 \text{ mA/V}$$

$$r_{\pi} = \frac{\beta}{g_m} = \frac{100}{20} = 5 \text{ K}\Omega$$

$$A_v = \frac{V_O}{V_S} = \frac{V_{\pi}}{V_S} \times \frac{V_O}{V_{\pi}}$$

$$= \frac{r_{\pi}}{r_{\pi} + R_S} \times -g_m (r_o \parallel R_C \parallel R_L)$$

$$= -\frac{5}{5 + 2.5} \times 20 (200 \parallel 20 \parallel 10)$$

$$= \underline{-86 \text{ V/V}}$$

5.135

Refer to Fig. P5.135

(a) For each transistor

$$V_{BB} = 15 \times \frac{47}{100 + 47} = 4.8 \text{ V}$$

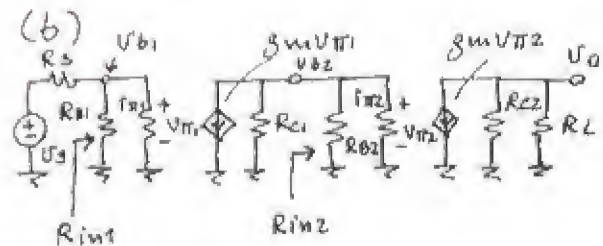
$$R_B = R_1 \parallel R_2 = 100 \parallel 47 = 32 \text{ K}\Omega$$

$$I_E = \frac{4.8 - 0.7}{3.9 + \frac{32}{101}} = 0.97 \text{ mA}$$

$$I_C = 0.99 \times 0.97 = \underline{0.96 \text{ mA}}$$

$$V_C = V_{CC} - I_C \times R_C$$

$$= 15 - 0.96 \times 6.8 = \underline{8.5 \text{ V}}$$



$$R_{B1} = R_{B2} = R_B = 32 \text{ K}\Omega$$

$$g_{m1} = g_{m2} = \frac{0.96}{0.025} = 38.4 \text{ mA/V}$$

$$r_{\pi 1} = r_{\pi 2} = \frac{100}{38.4} = 2.6 \text{ K}\Omega$$

$$R_{C1} = R_{C2} = 6.8 \text{ K}\Omega$$

$$r_{o1} = r_{o2} = \infty$$

$$(c) \quad R_{in1} = R_{B1} \parallel r_{\pi 1}$$

$$= 32 \parallel 2.6 = \underline{2.4 \text{ K}\Omega}$$

$$\frac{V_{b1}}{V_S} = \frac{R_{in1}}{R_S + R_{in1}}$$

$$= \frac{2.4}{5 + 2.4} = \underline{0.32 \text{ V/V}}$$

$$(d) \quad R_{in2} = R_{B2} \parallel r_{\pi 2}$$

$$= 32 \parallel 2.6 = \underline{2.4 \text{ K}\Omega}$$

CONT.

$$V_{b2} = -g_{m1} V_{\pi 1} (R_{c1} \parallel R_{in2})$$

$$= -38.4 V_{b1} (6.8 \parallel 2.4)$$

$$\frac{V_{b2}}{V_{b1}} = \underline{\underline{-68.1 \text{ V/V}}}$$

$$(e) V_o = -g_{m2} V_{\pi 2} (R_{c2} \parallel R_L)$$

$$= -38.4 V_{b2} (6.8 \parallel 12)$$

$$\frac{V_o}{V_{b2}} = \underline{\underline{-59.3 \text{ V/V}}}$$

$$(f) \frac{V_o}{V_s} = \frac{V_{b1}}{V_s} \times \frac{V_{b2}}{V_{b1}} \times \frac{V_o}{V_{b2}}$$

$$= 0.32 \times -68.1 \times -59.3$$

$$= \underline{\underline{1292 \text{ V/V}}}$$

5.136

Refer to the circuit in Fig. P5.136

$$R_{in} = (\beta + 1)(r_e + 250)$$

$$\beta = 100 \quad r_e = \frac{V_T}{I_E} = \frac{0.025}{0.1} = 250 \Omega$$

$$R_{in} = 101 \times (250 + 250)$$

$$= \underline{\underline{50.5 \text{ K}\Omega}}$$

$$\frac{V_b}{V_s} = \frac{R_{in}}{R_s + R_{in}} = \frac{50.5}{20 + 50.5}$$

$$= 0.72 \text{ V/V}$$

$$\frac{V_o}{V_b} = -\alpha \frac{(20 \parallel 20)}{(r_e + R_E)}$$

$$= -\frac{0.99 \times 10}{0.250 + 0.250} = \underline{\underline{-19.8 \text{ V/V}}}$$

Thus, $\frac{V_o}{V_s} = 0.72 \times -19.8 = \underline{\underline{-14.2 \text{ V/V}}}$

For $V_{be} = 5 \text{ mV}$, $V_e = 5 \text{ mV}$ also
(since $R_e = r_e = 250 \Omega$)

Thus,

$$V_b = 5 + 5 = 10 \text{ mV}$$

$$V_s = \frac{10 \text{ mV}}{0.72} = \underline{\underline{13.88 \text{ mV}}}$$

$$V_o = 13.88 \times 14.2 = \underline{\underline{197.2 \text{ mV}}}$$

5.137

$$(a) I_C = 0.99 \times 0.5 \text{ mA}$$

$$= 0.495 \text{ mA}$$

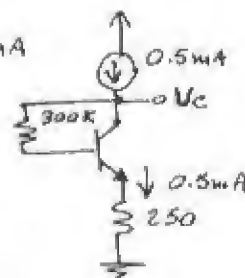
$$V_C = I_C R_E + V_{BE} \dots$$

$$+ I_B R_B$$

$$= 0.5 \times 0.175 + 0.7$$

$$+ 0.005 \times 300$$

$$= \underline{\underline{2.28 \text{ V}}}$$

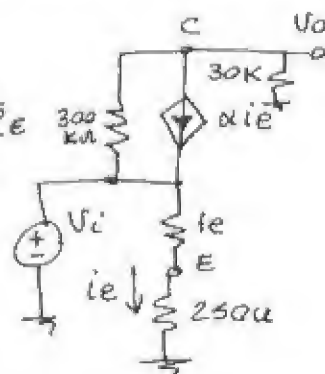


$$(b) i_e = \frac{V_i}{r_e + R_E}$$

$$r_e = \frac{V_T}{I_E} = 50 \Omega$$

$$\rightarrow i_e = \frac{V_i}{50 + 250}$$

$$i_e = \frac{V_i}{300}$$



Node equation at c:

$$\frac{V_o - V_i}{300 \text{ K}} + \alpha i_e + \frac{V_o}{30 \text{ K}} = 0$$

$$\frac{V_o - V_i}{300 \text{ K}} + \frac{\alpha V_i}{(250 + 50)} + \frac{V_o}{30 \text{ K}} = 0$$

$$\Rightarrow \frac{V_o}{V_i} = \underline{\underline{-90 \text{ V/V}}}$$

5.138

(a) Without R_e ,

$$A_v \approx -\frac{\beta (R_c \parallel R_L \parallel r_o)}{r_{\pi} + R_s}$$

CONT.

Since no value is specified for r_o (or V_A) we shall neglect its effect, thus

$$A_v = -\beta \frac{(R_c \parallel R_L)}{r_{\pi} + R_s}$$

Substituting $r_{\pi} = \beta/g_m$ yields

$$\begin{aligned} A_v &= -\frac{(R_c \parallel R_L)}{\frac{\beta}{\beta+1} \cdot \frac{1}{g_m} + \frac{R_s}{\beta}} \\ &= -\frac{(R_c \parallel R_L)}{r_e + \frac{R_s}{\beta}} \end{aligned}$$

Maximum gain is obtained at the high β ,

$$\begin{aligned} A_{vmax} &= -\frac{(R_c \parallel R_L)}{r_e \rightarrow \frac{0.050 + 10}{150}} \\ &= -8.57 (R_c \parallel R_L) \end{aligned}$$

The minimum gain is obtained for β at its lowest value

$$\begin{aligned} A_{vmin} &= -\frac{(R_c \parallel R_L)}{0.050 + \frac{10}{50}} \\ &= -4 (R_c \parallel R_L) \end{aligned}$$

$$\text{Thus, } \frac{A_{vmax}}{A_{vmin}} = \frac{8.57}{4} = \underline{\underline{2.14}}$$

(b) With R_e

$$\begin{aligned} A_v &= -\frac{\beta (R_c \parallel R_L)}{r_{\pi} (1 + g_m R_e) + R_s} \\ &= -\frac{(R_c \parallel R_L)}{\frac{1}{g_m} (1 + g_m R_e) + \frac{R_s}{\beta}} \end{aligned}$$

$$A_v = -\frac{(R_c \parallel R_L)}{\frac{1}{g_m} + R_e + \frac{R_s}{\beta}}$$

$$\frac{A_{vmax}}{A_{vmin}} = \frac{\frac{1}{g_m} + R_e + \frac{R_s}{\beta_{min}}}{\frac{1}{g_m} + R_e + \frac{R_s}{\beta_{max}}}$$

Thus,

$$1.2 = \frac{50 + R_e + \frac{10,000}{50}}{50 + R_e + \frac{10,000}{150}}$$

$$\Rightarrow R_e = \underline{\underline{550 \Omega}}$$

(c) For $\beta = 100$:

(i) Without R_e ,

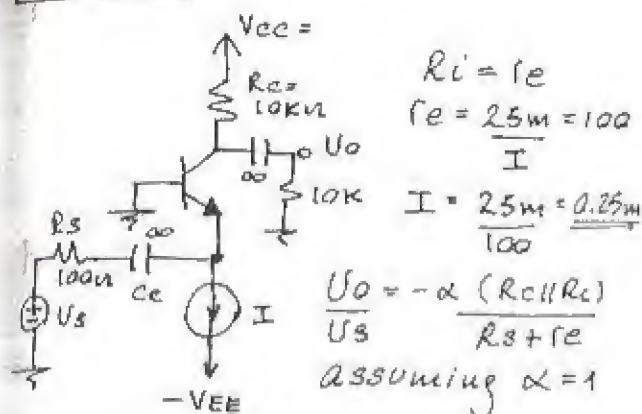
$$\begin{aligned} A_v &= -\frac{(R_c \parallel R_L)}{r_e + R_s/\beta} \\ &= -\frac{(R_c \parallel R_L)}{0.050 + 10/100} \\ &= -6.66 (R_c \parallel R_L) \end{aligned}$$

(ii) With $R_e = 550 \Omega$

$$\begin{aligned} A_v &\approx -\frac{(R_c \parallel R_L)}{0.050 + 0.550 + \frac{10}{100}} \\ &= -1.43 (R_c \parallel R_L) \end{aligned}$$

Thus including R_e reduces the gain by a factor of $\frac{6.66}{1.43} = \underline{\underline{4.6}}$

5.139



$$\frac{V_o}{V_s} = \frac{10 || 10}{(0.100) 2} = -25 \frac{V}{V}$$

$$= 9.64 K\Omega$$

$$\text{Select } R_c = \underline{9.1 K\Omega}$$

$$V_c = 0.45V$$

$$\begin{aligned} \frac{V_o}{V_s} &= \frac{R_i}{R_s + R_i} g_m (R_c || 1) \\ &= \frac{50}{50 + 50} \times 20 \times (9.1 || 1) \\ &= \underline{9 V/V} \end{aligned}$$

$$\text{For } V_{b \max} = 10mV$$

$$V_{s \max} = 20mV$$

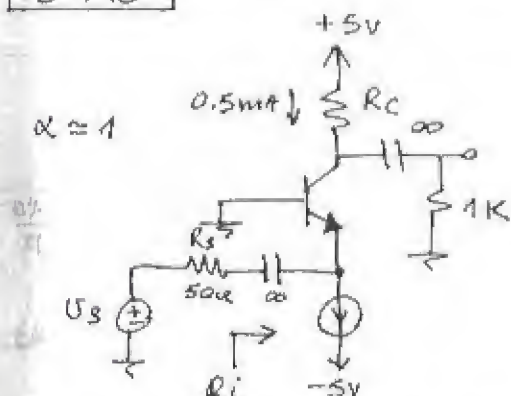
$$V_{c \max} = 180mV$$

Thus the collector voltage swings from

$$(0.45 - 0.18)V \text{ to } (0.45 + 0.18)V$$

i.e. from 0.27V to 0.63V

5.140



$$R_i = \frac{V_T}{I} = 50\Omega \Rightarrow I = \underline{0.5mA}$$

$$V_c = 5 - 0.5 R_c$$

$$V_{c \min} = V_c - 0.01 g_m (R_c || 1K)$$

To prevent saturation $V_{c \min} = 0$

$$\begin{aligned} 0 &= V_c - 0.01 \times 20 (R_c || 1) \\ &= 5 - 0.5 \frac{R_c}{R_c + 1} \end{aligned}$$

$$\begin{aligned} 5R_c + 5 - 0.5R_c^2 - 0.5R_c - 0.2R_c &= 0 \\ 0.5R_c^2 - 4.3R_c + 5 &= 0 \end{aligned}$$

$$R_c = \frac{4.3 + \sqrt{4.3^2 + 10}}{1}$$

5.141

Refer to Fig P5.141

$$R_i = r_e = \frac{V_T}{I_E} = \frac{V_T}{0.5} = \underline{50\Omega}$$

To find the voltage gain V_o/V_s first note that

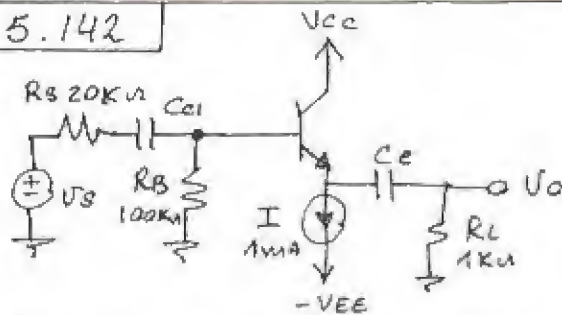
$$\frac{V_e}{V_s} = \frac{R_i}{R_s + R_i} = \frac{50}{50 + 50} = 0.5$$

Then,

$$\begin{aligned} \frac{V_c}{V_e} &= \alpha \times \frac{(\text{Total resistance at } c)}{r_e} \\ &\approx \frac{1 \times (100K\Omega || 1K\Omega)}{50\Omega} \\ &= 19.8 V/V \end{aligned}$$

$$\text{Thus, } \frac{V_o}{V_s} = 19.8 \times 0.5 = \underline{9.9 V/V}$$

5.142



$$V_A = 100 \Rightarrow r_o = \frac{V_A}{I_o} = \frac{100}{\frac{\beta \times I}{\beta + 1}}$$

$$r_o = 101 \text{ k}\Omega$$

$$(a) R_{in} = R_B \parallel [(\beta + 1)(r_e + (R_L \parallel r_o))]$$

$$R_{in} = 100 \text{ k}\Omega \parallel [(101)(25 + (1 \text{ k}\Omega \parallel 101 \text{ k}\Omega))]$$

$$R_{in} = \underline{50.6 \text{ k}\Omega}$$

$$\frac{U_b}{U_s} = \frac{R_{in}}{R_{in} + R_s} = \underline{0.717 \text{ V/V}}$$

$$\frac{U_o}{U_s} = \frac{U_b}{U_s} \cdot \frac{(R_L \parallel r_o)}{(R_L \parallel r_o) + r_e} = \underline{0.975 \text{ V/V}}$$

(b) The peak value of U_o occurs when the current flowing from ground through R_e equals the bias current I on a negative signal swing

$$\hat{U}_o = I = 1 \text{ mA}$$

$$\hat{U}_o = 1 \text{ V} \Rightarrow \hat{U}_s = \frac{1}{0.975} = \underline{1.025 \text{ V}}$$

$$U_{\pi} = U_s' \times \frac{(\beta + 1) r_e}{(\beta + 1) r_e + (\beta + 1)(R_L \parallel r_o)}$$

= : Where U_s' is

$$U_s' = U_s \times \frac{R_{in}}{R_{in} + R_s} = U_s \times 0.717$$

$$U_{\pi} = \frac{(1.025 \times 0.717) \times 101 \times 25}{101[25 + 990]}$$

$$= \underline{18.10 \text{ mV}}$$

$$(c) \hat{U}_{\pi} = 10 \text{ mV} \Rightarrow$$

$$U_s = \frac{10 \text{ m} \times 101[25 + 990]}{0.717 \times 101 \times 25}$$

$$= \underline{0.566 \text{ V}}$$

$$U_o = \frac{U_o}{U_s} \times 0.566 = \underline{0.552 \text{ V}}$$

$$(d) R_o = (r_e + \frac{R_s \parallel R_B}{\beta + 1}) \parallel r_o$$

$$= (25 + \frac{(20 \text{ k}\Omega \parallel 100 \text{ k}\Omega)}{101}) \parallel 101 \text{ k}\Omega$$

$$= \underline{190 \Omega}$$

Open circuit voltage gain

$$A_v|_{R_L = \infty} = \frac{R_B}{R_s + R_B} \cdot \frac{r_o}{r_o + r_e + \frac{R_s \parallel R_B}{\beta + 1}}$$

$$= \frac{100}{20 + 100} \cdot \frac{101 \text{ k}}{101 \text{ k} + 25 + \frac{(100 \parallel 20) \text{ k}}{101}}$$

$$= \underline{0.832 \text{ V/V}}$$

$$A_v = A_v|_{R_L = \infty} \times \frac{R_L}{R_L + R_o}$$

$$= 0.832 \times \frac{500}{500 + 190}$$

$$= \underline{0.603 \text{ V/V}}$$

5.143

Refer to Fig. P5.143

$$(a) I_E = \frac{9 - 0.7}{1 + 100 \parallel (\beta + 1)} \text{ CONT.}$$

$$\text{for } \beta = 40, I_E = \frac{8.3}{1 + \frac{100}{41}} = \underline{\underline{2.41 \text{ mA}}}$$

$$V_E = 1 \times 2.41 = \underline{\underline{2.41 \text{ V}}}$$

$$V_B = 2.41 + 0.7 = \underline{\underline{3.11 \text{ V}}}$$

$$\text{for } \beta = 200, I_E = \frac{8.3}{1 + \frac{100}{201}} = \underline{\underline{5.54 \text{ mA}}}$$

$$V_E = + \underline{\underline{5.54 \text{ V}}}$$

$$V_B = + \underline{\underline{6.24 \text{ V}}}$$

$$(b) R_i = 100 \text{ k}\Omega \parallel (\beta + 1)[r_e + (1 \parallel 1)]$$

$$= 100 \parallel (\beta + 1)[r_e + 0.5]$$

$$\text{For } \beta = 40, I_E = 2.41 \text{ mA}$$

$$\rightarrow r_e = 10.37 \text{ }\Omega$$

$$\text{thus } R_i = 100 \parallel 41 \times (0.01037 + 0.5)$$

$$= 100 \parallel 21$$

$$= \underline{\underline{17.30 \text{ }\Omega}}$$

$$\text{For } \beta = 200, I_E = 5.54 \text{ mA}$$

$$\rightarrow r_e = 4.51 \text{ }\Omega$$

$$\text{thus } R_i = 100 \parallel 201(0.0045 + 0.5)$$

$$= 100 \parallel 101.4$$

$$= \underline{\underline{50.3 \text{ k}\Omega}}$$

$$(c) \frac{V_o}{V_s} = \frac{V_b}{V_s} \cdot \frac{V_o}{V_b}$$

$$= \frac{R_i}{R_s + R_i} \cdot \frac{(1 \parallel 1)}{(1 \parallel 1) + r_e}$$

$$\text{For } \beta = 40,$$

$$\frac{V_o}{V_s} = \frac{17.3}{10 + 17.3} \times \frac{0.5}{0.5 + 0.01037}$$

$$= \underline{\underline{0.621 \text{ V/V}}}$$

$$\text{For } \beta = 200,$$

$$\frac{V_o}{V_s} = \frac{50.3}{10 + 50.3} \cdot \frac{0.5}{0.5 + 0.0045}$$

$$= \underline{\underline{0.827 \text{ V/V}}}$$

5.144

Refer to Fig. P5.144

$$I_E = \frac{5 - 0.7}{3.3 + \frac{100}{101}} = \underline{\underline{1.00 \text{ mA}}}$$

$$r_e = \frac{25}{1.00} = 25 \text{ }\Omega$$

$$R_i = (\beta + 1)[r_e + (3.3 \parallel 1)]$$

$$= \underline{\underline{80.0 \text{ k}\Omega}}$$

$$\frac{V_o}{V_s} = \frac{V_b}{V_s} \cdot \frac{V_o}{V_b} = \frac{R_i}{R_s + R_i} \cdot \frac{(3.3 \parallel 1)}{r_e + (3.3 \parallel 1)}$$

Thus,

$$\frac{V_o}{V_s} = \frac{80}{100 + 80} \times \frac{(3.3 \parallel 1)}{0.025 + (3.3 \parallel 1)}$$

$$= \underline{\underline{0.430 \text{ V/V}}}$$

$$\frac{V_o}{V_i} = \frac{V_o / R_L}{V_s / (R_s + R_i)}$$

$$= \frac{V_o}{V_s} \cdot \frac{(R_s + R_i)}{R_L}$$

$$= 0.43 \times \frac{(100 + 80)}{1}$$

$$= \underline{\underline{77.4 \text{ A/A}}}$$

$$R_{out} = 3.3 \parallel \left[r_e + \frac{100}{\beta + 1} \right]$$

$$= 3.3 \parallel \left[0.025 + \frac{100}{101} \right]$$

$$= \underline{\underline{0.776 \text{ k}\Omega}}$$

5.145

Refer to Fig 5.63(a)

$$R_o = 10 \parallel [r_e + 10 \text{ k}\Omega / (\beta + 1)]$$

CONT.

$$R_o = \frac{V_A}{I_c} \parallel \left[\frac{V_T}{I_E} + \frac{10K\Omega}{\beta+1} \right]$$

$$\begin{aligned} R_o &= \frac{125}{0.99 \times 2.5} \parallel \left[\frac{0.025}{2.5} + \frac{10}{100+1} \right] \\ &= 50.5 \parallel [0.010 + 0.099] \\ &= 0.109K\Omega = \underline{\underline{109\mu}} \end{aligned}$$

With no load:

$$\begin{aligned} R_i &= (\beta+1)[r_e + r_o] \\ \text{For } \beta &= 100, r_e = 10\mu, r_o = 50.5K\Omega \\ R_i &= 101 \times (0.010 + 50.5) \\ &= \underline{\underline{5.1M\Omega}} \end{aligned}$$

$$\begin{aligned} \frac{U_o}{U_s} &= \frac{U_b}{U_s} \cdot \frac{U_o}{U_b} = \frac{R_i}{R_s + R_i} \times \frac{r_o}{r_o + r_e} \\ &= \frac{5100}{10 + 5100} \cdot \frac{50.5}{50.5 + 0.01} \\ &= \underline{\underline{0.988V/V}} \end{aligned}$$

With $R_L = 1K\Omega$:

$$\begin{aligned} \frac{U_o}{U_s} &= 0.988 \times \frac{R_L}{R_L + R_o} \\ &= 0.988 \times \frac{1}{1 + 0.109} = \underline{\underline{0.890V/V}} \end{aligned}$$

Largest negative output signal occurs when the BJT cuts off, thus:

$$\begin{aligned} U_{o\min} &= -2.5mA \times 1K\Omega \\ &= \underline{\underline{-2.5V}} \end{aligned}$$

Largest positive output signal occurs when $U_B = +3.4V$.

The corresponding value of U_E is $\approx 3.4 - 0.7 = +2.7V$ (where we have neglected the signal component of U_{BE})

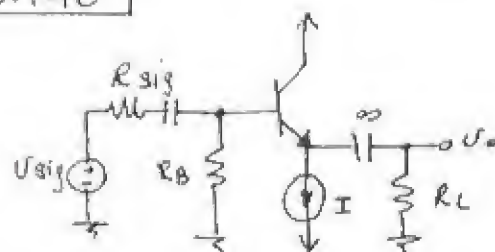
Now, the DC level at the emitter with zero input signal is

$$\begin{aligned} V_E &= -10K\Omega \times I_B - 0.7 \\ &= -10 \times \frac{2.7}{101} - 0.7 \\ &\approx -0.97V \end{aligned}$$

Thus the signal component is:

$$\begin{aligned} U_{e\max} &= U_E - V_E \\ &= 2.5 - (-0.97) \\ &= \underline{\underline{3.47V}} \end{aligned}$$

5.146



$$\begin{aligned} G_o|_{R_L \rightarrow \infty} &= \frac{R_B}{R_{sig} + R_B} \cdot \frac{r_o}{R_{sig} \parallel R_B + r_e + r_o} = 0.99 \\ &\approx 1 \text{ for very large } r_o \end{aligned}$$

$$\Rightarrow \frac{R_B}{R_{sig} + R_B} = 0.99$$

$$\rightarrow \frac{R_B}{10K + R_B} = 0.99 \Rightarrow R_B = 990K\Omega$$

$$R_{out} = r_o \parallel (r_e + R_s \parallel R_B)$$

$$\text{for } r_o \text{ large: } R_{out} \approx \frac{r_e + R_s \parallel R_B}{\beta+1}$$

$$r_e + \frac{(10 \parallel 990)K}{\beta+1} = 200\mu$$

$$r_e + \frac{(20 \parallel 990)K}{\beta+1} = 300\mu$$

CONT.

Then,

$$r_e + \frac{9.9K}{\beta+1} = 200 \quad (1)$$

$$r_e + \frac{19.6K}{\beta+1} = 300 \quad (2)$$

Solving Eqs. (1) and (2)

$$\beta+1 = 97 \Rightarrow \beta = 96$$

$$\text{and } r_e = 98 \Omega$$

If: $R_{sig} = 30K\Omega$ and $R_L = 1K\Omega$

$$G_U = \frac{R_B}{R_{sig} + R_B} \cdot \frac{(r_o \parallel R_L)}{\frac{R_{sig} \parallel R_B}{\beta+1} + r_e + (r_o \parallel R_L)}$$

If r_o is large:

$$\begin{aligned} G_U &= \frac{R_B}{R_{sig} + R_B} \cdot \frac{R_L}{\frac{R_{sig} \parallel R_B}{\beta+1} + r_e + R_L} \\ &= \frac{990}{30 + 990} \cdot \frac{1}{\frac{(30 \parallel 990) + 0.098 + 1}{97}} \\ &= \underline{\underline{0.7 \text{ V/V}}} \end{aligned}$$

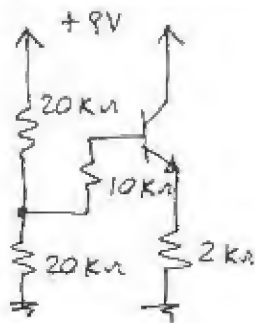
5.147

(a) DC Analysis

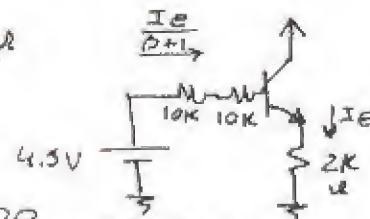
$$\begin{aligned} I_E &= \frac{4.5 - 0.7}{2 + \frac{10+10}{101}} \\ &= \underline{\underline{1.73 \text{ mA}}} \end{aligned}$$

$$I_C = 0.99 \times 1.73 = \underline{\underline{1.71 \text{ mA}}}$$

$$g_m = \frac{I_C}{V_T} = 68.5 \text{ mA/V}$$

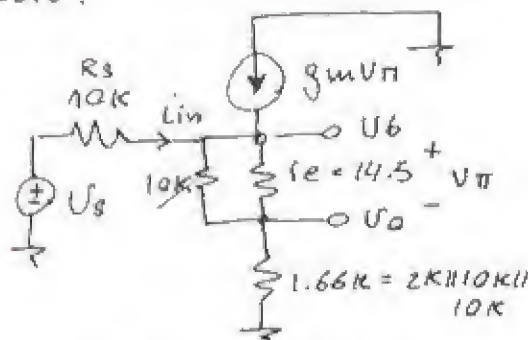


$$r_e = \frac{V_T}{I_E} = \underline{\underline{14.5 \Omega}}$$



$$r_{\pi} = \frac{\beta}{g_m} = \frac{100}{68.5} = \underline{\underline{1.46 K\Omega}}$$

(b) Simplified equivalent circuit:



$$v_o \approx 1.66K \times \left(\frac{v_{\pi}}{14.5} \right) = 114.48 v_{\pi}$$

$$\frac{v_{\pi}}{14.5} = i_{in} + 68 \times 10^{-3} v_{\pi}$$

$$\rightarrow v_{\pi} \left(\frac{1}{14.5} - 68 \times 10^{-3} \right) = i_{in}$$

$$i_{in} = \frac{v_{\pi}}{1035K}$$

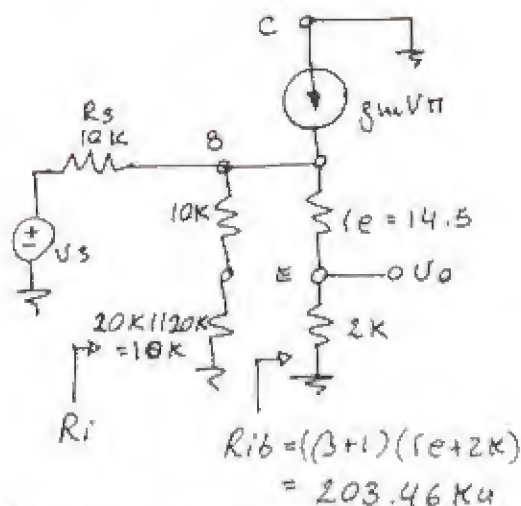
$$v_b = v_{\pi} + v_o = 115.48 v_{\pi}$$

$$R_i = \frac{v_b}{i_{in}} = \frac{115.48 v_{\pi}}{v_{\pi} / 1.035} = \underline{\underline{120 K\Omega}}$$

$$\begin{aligned} \frac{v_o}{v_s} &= \frac{v_b}{v_s} \cdot \frac{v_o}{v_b} = \frac{R_i}{R_i + R_s} \cdot \frac{114.48 v_{\pi}}{115.48 v_{\pi}} \\ &= \frac{120}{120 + 10} \times \frac{114.48}{115.48} = \underline{\underline{0.92 \text{ V/V}}} \end{aligned}$$

(c) With C_B open-circuited so that bootstrapping is eliminated, we obtain the following equivalent circuit model.

CONT.



$$R_i = (10K + 20K \parallel 20K) \parallel 203.46K$$

$$= 18.21K\Omega \text{ (much lower than the value obtained with bootstrap.)}$$

$$V_o = \frac{V_{\pi}}{14.5} \times 2K = 138 \times V_{\pi}$$

$$V_b = V_o + V_{\pi} = (1 + 138)V_{\pi} = 139V_{\pi}$$

$$\frac{V_o}{V_s} = \frac{V_b}{V_s} \cdot \frac{V_o}{V_b} = \frac{R_i}{R_s + R_i} \cdot \frac{V_o}{V_b}$$

$$= \frac{18.21}{10 + 18.21} \cdot \frac{138}{139} = 0.64 V/V$$

Much lower than the value obtained with bootstrapping. This is due to the lower R_i . Bootstrapping raises the component of input resistance due to the base biasing network.

5.148

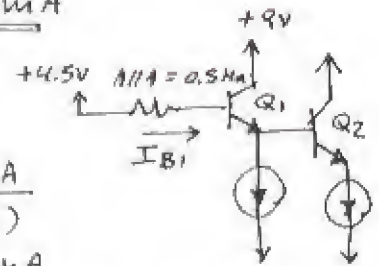
Refer to the circuit in Fig P5.148

(a) $I_{E2} = 5mA$
 $\beta_1 = 50, \beta_2 = 100$

$$I_{E1} = 50\mu A + I_{B2}$$

$$= 50 + \frac{I_{E2}}{\beta_2 + 1} = 50 + \frac{5000}{101}$$

$$\approx 0.1mA$$



$$I_{B1} = \frac{0.1mA}{(50 + 1)} = 1.96\mu A$$

$$V_{B1} = 4.5 - 0.5 \times 19.6 = 3.52V$$

$$V_{B2} = 3.52 - 0.7 = 2.82V$$

(b) Refer to Fig. P.5.148

$$\frac{V_o}{V_{B2}} = \frac{R_L}{R_L + r_{e2}}$$

$$R_L = 1K\Omega, r_{e2} = \frac{25}{5} = 5\Omega$$

$$\frac{V_o}{V_{B2}} = \frac{1}{1 + 0.005} = 0.995 V/V$$

$$R_{ib2} = (\beta_2 + 1)(r_{e2} + R_L)$$

$$= (101) \times (1.005)$$

$$= 101.5K\Omega$$

(c) $\frac{V_{e1}}{V_{B1}} = \frac{R_{ib2}}{R_{ib2} + r_{e1}}$
 $r_{e1} = \frac{V_T}{I_{E1}} = \frac{25mV}{100\mu A}$

$$\rightarrow \frac{V_{e1}}{V_{B1}} = \frac{101.5}{101.5 + 0.25} = 0.997 V/V$$

$$R_i = 1M\Omega \parallel 1M\Omega \parallel (\beta_1 + 1)(r_{e1} + R_{ib2})$$

$$= 1 \parallel 1 \parallel 51 \times (0.25 + 101.5)K\Omega$$

$$= 1 \parallel 1 \parallel 5.2K\Omega$$

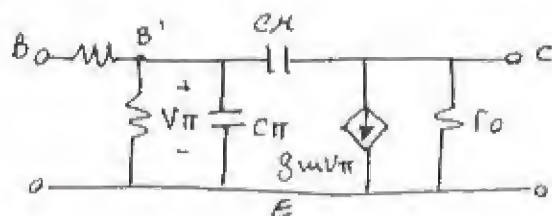
$$= 0.499M\Omega = 499K\Omega$$

(d) $\frac{V_{B1}}{V_s} = \frac{R_i}{R_s + R_i} = \frac{499}{100 + 499} = 0.833 V/V$

CONT.

$$\begin{aligned}
 (e) \frac{V_o}{V_s} &= \frac{V_{b1}}{V_s} \cdot \frac{V_{e1}}{V_{b1}} \cdot \frac{V_o}{V_{e1}} \\
 &= 0.833 \times 0.997 \times 0.995 \\
 &= \underline{\underline{0.826 \text{ V/V}}}
 \end{aligned}$$

5.149



$$R_B = 100 \text{ k}\Omega$$

$$g_m = \frac{I_C}{V_T} = \frac{0.5 \text{ mA}}{25 \text{ mV}} = \underline{\underline{20 \text{ mA/V}}}$$

$$r_{\pi} = \frac{\beta_0}{g_m} = \frac{100}{20} = \underline{\underline{5 \text{ k}\Omega}}$$

$$r_o = \frac{V_A}{I_C} = \frac{50 \text{ V}}{0.5 \text{ mA}} = \underline{\underline{100 \text{ k}\Omega}}$$

$$C_{\mu} = \frac{C_{j0}}{\left(1 + \frac{V_{CB}}{V_{0c}}\right)^{0.5}} = \frac{30}{\left(1 + \frac{2}{0.75}\right)^{0.5}} = \underline{\underline{15.7 \text{ fF}}}$$

$$C_{je} \approx 2C_{je0} = 2 \times 20 = 40 \text{ fF}$$

$$C_{de} = r_F g_m = 30 \times 10^{-12} \times 20 \times 10^3 = 600 \text{ fF}$$

$$C_{\pi} = C_{je} + C_{de} = \underline{\underline{0.640 \text{ pF}}}$$

$$\begin{aligned}
 f_T &= \frac{g_m}{2\pi(C_{\pi} + C_{\mu})} = \frac{20 \times 10^{-3}}{2\pi(0.64 + 0.016) \times 10^{-12}} \\
 &= \underline{\underline{4.85 \text{ GHz}}}
 \end{aligned}$$

5.150

$$|h_{fe}| \approx f_T / f$$

$$\begin{aligned}
 \bullet \text{ At } I_C = 0.2 \text{ mA}, |h_{fe}| = 2.5 \\
 \text{at } f = 500 \text{ kHz, thus:}
 \end{aligned}$$

$$f_T = 2.5 \times 500 = \underline{\underline{1.25 \text{ GHz}}}$$

$$\begin{aligned}
 \bullet \text{ At } I_C = 1.0 \text{ mA}, |h_{fe}| = 11.6 \\
 \text{at } f = 500 \text{ kHz, thus:} \\
 f_T = 11.6 \times 500 = \underline{\underline{5.8 \text{ GHz}}}
 \end{aligned}$$

$$f_T = \frac{g_m}{2\pi(C_{\pi} + C_{\mu})}$$

$$C_{\pi} + C_{\mu} = \frac{g_m}{2\pi f_T} \rightarrow C_{\pi} = \frac{g_m}{2\pi f_T} - C_{\mu}$$

$$\begin{aligned}
 C_{\pi} (I_C = 0.2 \text{ mA}) &= \frac{8 \times 10^{-3} - 0.05 \times 10^{-12}}{2\pi \times 1.25 \times 10^9} \\
 &= \underline{\underline{0.9686 \text{ pF}}}
 \end{aligned}$$

$$\begin{aligned}
 C_{\pi} (I_C = 1.0 \text{ mA}) &= \frac{40 \times 10^{-3} - 0.05 \times 10^{-12}}{2\pi \times 5.8 \times 10^9} \\
 &= \underline{\underline{1.0476 \text{ pF}}}
 \end{aligned}$$

$$\text{Since } C_{\pi} = C_{je} + r_F g_m,$$

$$C_{je} + 8 \times 10^{-3} r_F = 0.9686 \times 10^{-12} \quad (1)$$

$$C_{je} + 40 \times 10^{-3} r_F = 1.0476 \times 10^{-12} \quad (2)$$

$$\text{Solving Eqs. (1) and (2)}$$

$$\text{together yields,}$$

$$C_{je} = \underline{\underline{0.95 \text{ pF}}}, r_F = \underline{\underline{247 \text{ ps}}}$$

5.151

$$\begin{aligned}
 f_T &= \frac{g_m}{2\pi(C_{\pi} + C_{\mu})} \\
 &= \frac{80 \times 10^{-3}}{2\pi(10 + 1) \times 10^{-12}} \\
 &= \underline{\underline{4.24 \text{ GHz}}}
 \end{aligned}$$

$$\begin{aligned}
 f_{\beta} &= f_T / \beta_0 = (4.24 / 150) \times 10^9 \\
 &= \underline{\underline{28.26 \text{ MHz}}}
 \end{aligned}$$

5.152

$$\text{At } I_C = 2 \text{ mA the diffusion part of } C_{\pi} \text{ is: } 10^{-2} = 8 \text{ pF}$$

CONT.

At $I_c = 0.2 \text{ mA}$ the diffusion capacitance becomes 0.8 pF and thus,

$$C_\pi = 0.8 + 2 = 2.8 \text{ pF}$$

and:

$$f_T = \frac{g_m}{2\pi(C_\pi + C_\mu)} = \frac{8 \times 10^{-3}}{2\pi(2.8 + 1) \times 10^{-12}} = \underline{\underline{335 \text{ MHz}}}$$

5.153

$$\omega_T = g_m / (C_\pi + C_\mu)$$

$$2\pi \times 5 \times 10^9 = \frac{20 \times 10^{-3}}{(C_\pi + 0.1) \times 10^{-12}}$$

$$C_\pi + 0.1 = \frac{20}{10\pi} = 0.64 \text{ pF}$$

$$C_\pi = \underline{\underline{0.54 \text{ pF}}}$$

$$g_m = \underline{\underline{20 \text{ mA/V}}}$$

$$r_\pi = \beta / g_m = 150 / 20 = \underline{\underline{7.5 \text{ k}\Omega}}$$

$$f_\beta = f_T / \beta = \frac{5 \times 10^9}{150} = \underline{\underline{33.3 \text{ MHz}}}$$

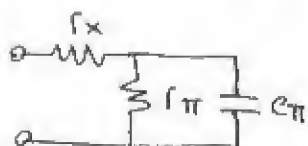
5.154

$|u_{fe}|$ becomes 20 at:

$$f_T / 20 = \frac{1 \times 10^9}{20} = \underline{\underline{50 \text{ MHz}}}$$

$$f_\beta = f_T / \beta_0 = \frac{1000 \text{ MHz}}{200} = \underline{\underline{5 \text{ MHz}}}$$

5.155



$$Z = r_x + \frac{1}{\frac{1}{r_\pi} + j\omega C_\pi}$$

$$= r_x + \frac{r_\pi}{1 + j\omega C_\pi r_\pi}$$

$$Z = r_x + \frac{r_\pi}{1 + j(\omega/\omega_\beta)}$$

$$= r_x + \frac{r_\pi (1 - j\omega/\omega_\beta)}{1 + (\omega/\omega_\beta)^2}$$

$$= r_x + \frac{r_\pi}{1 + (\omega/\omega_\beta)^2} - j \cdot \frac{r_\pi (\omega/\omega_\beta)}{1 + (\omega/\omega_\beta)^2}$$

$$\text{Re}[Z] = r_x + \frac{r_\pi}{1 + (\omega/\omega_\beta)^2}$$

For $\text{Re}[Z]$ to be an estimate of r_x good to within 10% we must keep

$$\frac{r_\pi}{1 + (\omega/\omega_\beta)^2} \leq \frac{r_x}{10}$$

But $r_x \leq r_\pi / 10$

Thus,

$$\frac{r_\pi}{1 + (\omega/\omega_\beta)^2} \leq \frac{r_\pi}{100}$$

$$1 + (\omega/\omega_\beta)^2 \geq 100$$

or $\omega \geq 10 \omega_\beta$ (approx.)

5.156

See completed table below

CONT.

	I_E (mA)	r_e (Ω)	g_m (mA/V)	r_π (k Ω)	β_0
(a)	1	25	40	2.5	100
(b)	1	25	40	3.13	125.3
(c)	0.99	25.3	39.6	2.525	100
(d)	10	2.5	400	0.25	100
(e)	0.1	250	4	25	100
(f)	1.0	25	40	0.25	10
(g)	1.25	20	50	0.20	10

CONT.	f_T (MHz)	C_π (pF)	C_μ (pF)	f_β (MHz)
(a)	400	2	13.9	4
(b)	501.3	2	10.7	4
(c)	400	2	13.8	4
(d)	400	2	157	4
(e)	100	2	4.4	1
(f)	400	2	13.9	40
(g)	800	1	9	80

5.157

From Example 5.18:

$$I = 2\text{mA}, \beta = 100, f_T = 800\text{MHz}$$

$$R_B = 50\text{k}\Omega, R_C = 4\text{k}\Omega, r_x = 50\Omega$$

$$V_A = 100, C_\mu = 1\text{pF}, R_{sig} = 5\text{k}\Omega$$

$$R_L = 5\text{k}\Omega$$

$$g_m = \frac{2\text{mA}}{25\text{mV}} = \frac{80\text{mA}}{\text{V}}$$

$$r_\pi = \frac{\beta_0}{g_m} = \frac{100}{80\text{mA/V}} = 1250\Omega$$

$$r_o = \frac{V_A}{I_C} = \frac{100\text{V}}{2\text{mA}} = 50\text{k}\Omega$$

$$C_\pi + C_\mu = \frac{g_m}{\omega_T} = \frac{80 \times 10^{-3}}{2\pi \times 800 \times 10^6} = 16\text{pF}$$

$$C_\mu = 1\text{pF} \Rightarrow C_\pi = 15\text{pF}$$

$$A_M = -\frac{R_B}{R_B + R_{sig}} \cdot \frac{r_\pi \times g_m R_L'}{r_\pi + r_x + (R_B \parallel R_{sig})}$$

$$\text{where } R_L' = r_o \parallel R_C \parallel R_L$$

$$= (50 \parallel 4 \parallel 5)\text{k}\Omega$$

$$= 2.1\text{k}\Omega$$

$$A_M = \frac{-50}{50+5} \cdot \frac{1250 \times 168}{1250+50+(50 \parallel 5)\text{k}\Omega}$$

$$\text{where } 168 = g_m \times R_L'$$

$$= 80 \times 10^{-3} \times 2.1 \times 10^3$$

$$\text{Then: } A_M = -32.6 //$$

$$20 \log |A_M| = \underline{\underline{30.3\text{dB}}}$$

$$C_{in} = C_\pi + C_\mu (1 + g_m R_L')$$

$$= 15 + 1(1 + 168) = 184\text{pF}$$

$$R'_{sig} = r_\pi \parallel [r_x + (R_B \parallel R_{sig})]$$

$$= 1250 \parallel [50 + (50\text{k} \parallel 5\text{k})]$$

$$= 983\Omega$$

$$f_H = \frac{1}{2\pi C_{in} R'_{sig}} = \frac{1}{2\pi \times 184 \times 10^{-12} \times 983}$$

$$= \underline{\underline{880\text{kHz}}}$$

Gain-bandwidth product

$$GB = |A_M| \times f_H = 32.6 \times 880 \times 10^3$$

$$= \underline{\underline{29 \times 10^6}}$$

Previously, in example 5.18

$$GB = 39 \times 754 \times 10^3 = 29 \times 10^6$$

Thus, the designer traded gain for bandwidth by increasing I . However, by doubling I the dissipation increased by a factor of 2, since:

$$\text{Power} = \frac{I \times V_{supply}}{2}$$

5.158

Refer to Fig. 5.71(a)

$$R_B \gg R_{sig}, r_x \ll R_{sig}$$

$$R_{sig} \gg r_\pi, g_m R_L' \gg 1$$

$$g_m R_L' C_\mu \gg C_\pi$$

CONT.

$$A_M = \underbrace{\frac{-R_B}{R_B + R_{sig}}}_{(4)} \cdot \frac{r_\pi \cdot g_m \cdot R_L'}{\underbrace{r_\pi + r_x + (R_{sig} \parallel R_B)}_{(2) \text{ and } (3)}}$$

- ① = R_{sig} , since $R_B \gg R_{sig}$
 ② = R_{sig} , since $R_{sig} \gg r_x$
 ③ = R_{sig} , since $R_{sig} \gg r_\pi$
 ④ = 1, since $R_B \gg R_{sig}$

Thus,

$$A_M = -\frac{r_\pi \cdot g_m \cdot R_L'}{R_{sig}}$$

but $r_\pi = \frac{\beta}{g_m}$

$$\Rightarrow A_M = -\frac{\beta R_L'}{R_{sig}} \quad \text{Q.E.D.}$$

(b) $f_H = \frac{1}{2\pi \cdot C_{in} \cdot R'_{sig}}$

$$C_{in} = C_\pi + C_x \underbrace{(1 + g_m R_L')}_{(1)}$$

(2)

- ① = $g_m R_L'$, since $R_L' \gg 1$
 ② = $C_x g_m R_L'$, since $C_x g_m R_L' \gg C_\pi$

$$\Rightarrow C_{in} = C_x \cdot g_m \cdot R_L'$$

$$R'_{sig} = r_\pi \parallel [r_x + \underbrace{(R_B \parallel R_{sig})}_{(1)}]$$

(2)

(3)

- ① = R_{sig} , since $R_B \gg R_{sig}$
 ② = R_{sig} , since $R_{sig} \gg r_x$
 ③ = r_π , since $R_{sig} \gg r_\pi$

$$\Rightarrow R'_{sig} = r_\pi$$

Thus,

$$f_H = \frac{1}{2\pi \cdot C_x \cdot g_m \cdot R_L' \cdot r_\pi}$$

Q.E.D.

(c)

$$GB = |A_M| \times f_H = \beta \frac{R_L'}{R_{sig}} \cdot \frac{1}{2\pi C_x \beta R_L'}$$

$$= \frac{1}{2\pi C_x R_{sig}} \quad \text{Q.E.D.}$$

For: $C_x = 1\text{pF}$ and $R_{sig} = 25\text{K}\Omega$

$$GB = \frac{1}{2\pi \times 10^{-12} \times 25 \times 10^3} = 6.36 \times 10^6$$

For: $I_C = 1\text{mA}$, $\beta = 100$, $R_{sig} = 25\text{K}\Omega$

1) If $R_L' = 25\text{K}\Omega$

$$A_M = -100 \cdot \frac{25\text{K}}{25\text{K}} = -100$$

$$20 \log |100| = 40\text{dB}$$

$$f_H = \frac{1}{2\pi \times 10^{-12} \times 100 \times 25 \times 10^3}$$

$$= 63.6\text{KHz}$$

2) If $R_L' = 2.5\text{K}\Omega$

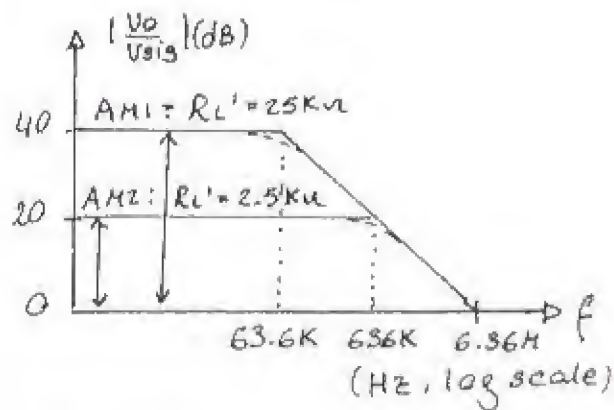
$$A_M = -100 \cdot \frac{2.5\text{K}}{25\text{K}} = -10$$

$$20 \log |10| = 20$$

CONT.

$$f_H = \frac{1}{2\pi \times 10^{-12} \times 100 \times 2.5 \cdot 10^3}$$

$$f_H = \underline{\underline{636 \text{ KHz}}}$$



$$GP = 6.36 \times 10^6 = A_M \times f_H$$

when $A_M = 1 \Rightarrow f_H = \underline{\underline{6.36 \cdot 10^6 \text{ Hz}}}$

$$R_L' = \frac{1}{2\pi (6.36 \times 10^6) C_A \times \beta}$$

$\downarrow \quad \quad \quad \downarrow$
 $1 \times 10^{-12} \quad 100$

$$R_L' = \underline{\underline{250\Omega}}$$

5.159

Refer to Fig. P5.159

$$R_{in} = R_1 \parallel R_2 \parallel (1 + \beta R_E)$$

where $R_1 = 33K\Omega$, $R_2 = 22K\Omega$

Next \rightarrow

CONT.

$$\begin{aligned}
 r_x &= 50 \text{ and,} \\
 r_{\pi} &= \frac{\beta_0}{g_m} = \frac{120}{0.3 \times 40} = \frac{120}{12} = 10 \text{ k}\Omega \\
 R_{in} &= 33 \parallel 22 \parallel 10.05 = \underline{5.7 \text{ k}\Omega} \\
 A_M &= -\frac{R_{in}}{R_{in} + R_s} \cdot \frac{r_{\pi}}{r_{\pi} + r_x} \cdot g_m (R_c \parallel R_L \parallel r_o) \\
 &= -\frac{5.7}{5.7 + 5} \cdot \frac{10}{10 + 0.05} \cdot 12 (4.7 \parallel 5.6 \parallel 300) \\
 &= \underline{-16.11 \text{ V/V}}
 \end{aligned}$$

$$\begin{aligned}
 R'_{sig} &= r_{\pi} \parallel [r_x + (R_1 \parallel R_2 \parallel R_{sig})] \\
 &= 10 \text{ k}\Omega \parallel [50 + (33 \parallel 22 \parallel 5) \text{ k}\Omega] \\
 &= \underline{2.69 \text{ k}\Omega}
 \end{aligned}$$

$$\begin{aligned}
 R'_L &= r_o \parallel R_c \parallel R_L = 300 \parallel 4.7 \parallel 5.6 (\text{k}\Omega) \\
 &= 2.53 \text{ k}\Omega
 \end{aligned}$$

$$\begin{aligned}
 C_{\pi} + C_{\mu} &= \frac{g_m}{2\pi \cdot f_T} = \frac{12 \cdot 10^{-3}}{2\pi \times 700 \cdot 10^6} \\
 &= 2.73 \text{ pF}
 \end{aligned}$$

$$\begin{aligned}
 C_{\pi} &= (2.73 - 1) \text{ pF} \\
 &= 1.73 \text{ pF}
 \end{aligned}$$

$$\begin{aligned}
 C_{in} &= C_{\pi} + C_{\mu} (1 + g_m R'_L) \\
 &= 1.73 \text{ p} + 1 \text{ p} (1 + 12 \times 2.53) \\
 &= 33 \text{ pF}
 \end{aligned}$$

$$\begin{aligned}
 f_H &= 1 / (2\pi C_{in} R'_{sig}) \\
 &= 1 / (2\pi \times 33 \cdot 10^{-12} \times 2.69 \cdot 10^3) \\
 &= \underline{1.79 \text{ MHz}}
 \end{aligned}$$

5.160

$$\begin{aligned}
 R_{in} &= R_1 \parallel R_2 \parallel r_{\pi} \\
 \text{where } r_{\pi} &= \frac{\beta}{g_m} \text{ and } g_m = \frac{I_C}{V_T} \\
 g_m &= \frac{0.8}{0.025} = 32 \text{ mA/V}
 \end{aligned}$$

$$r_{\pi} = \frac{200}{32} = 6.25 \text{ k}\Omega$$

$$R_{in} = 68 \parallel 27 \parallel 6.25 = 4.72 \text{ k}\Omega$$

$$R'_L = R_c \parallel R_L = 4.7 \parallel 10 = 3.2 \text{ k}\Omega$$

$$\begin{aligned}
 A_M &= \frac{R_{in}}{R_s + R_{in}} \times -g_m R'_L \\
 &= \frac{-4.72}{10 + 4.72} \times 32 \times 3.2 \\
 &= \underline{-32.8 \text{ V/V}}
 \end{aligned}$$

$$\begin{aligned}
 C_T &= C_{\pi} + C_{\mu} (1 + g_m R'_L) \\
 \text{where } C_{\pi} + C_{\mu} &= \frac{g_m}{2\pi f_T} = \frac{32 \times 10^{-3}}{2\pi \times 10^9} \\
 &= 5.1 \text{ pF}
 \end{aligned}$$

$$C_{\pi} = 5.1 - 0.8 = 4.3 \text{ pF}$$

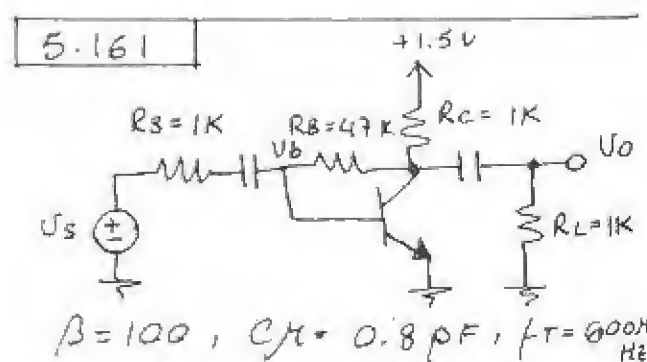
$$\begin{aligned}
 C_T &= 4.3 + 0.8 (1 + 32 \times 3.2) \\
 &= 87 \text{ pF}
 \end{aligned}$$

The resistance seen by C_T is R_T ,

$$\begin{aligned}
 R_T &= r_{\pi} \parallel R_1 \parallel R_2 \parallel R_s \\
 &= 6.25 \parallel 68 \parallel 27 \parallel 10 = 3.2 \text{ k}\Omega
 \end{aligned}$$

Thus

$$\begin{aligned}
 f_H &\approx \frac{1}{2\pi C_T R_T} \\
 &= \frac{1}{2\pi \times 87 \times 10^{-12} \times 3.2 \times 10^3} \\
 &= \underline{572 \text{ kHz}}
 \end{aligned}$$



CONT.

$$\begin{aligned}
 (a) \quad 1.5V &= 1K(I_C + I_B) + 47K \cdot I_B \\
 &\quad + 0.7V \\
 &= I_C + \frac{I_C}{\beta} + 47 \frac{I_C}{\beta} + 0.7 \\
 I_C &= \frac{0.8}{1 + \frac{48}{\beta}} = \frac{0.8}{1 + \frac{48}{100}} = \underline{\underline{0.54mA}}
 \end{aligned}$$

$$\begin{aligned}
 (b) \quad g_m &= \frac{I_C}{V_T} = 40 \times 0.54 = \underline{\underline{21.6 \frac{mA}{V}}} \\
 r_{\pi} &= \frac{\beta}{g_m} = \frac{100}{21.6} = \underline{\underline{4.63K\Omega}}
 \end{aligned}$$

$$\begin{aligned}
 (c) \quad V_o &\approx -g_m (R_C \parallel R_L) \cdot V_b \\
 &= -21.6 (1 \parallel 1) V_b \\
 &= -10.8 V_b \\
 \Rightarrow \frac{V_o}{V_b} &= \underline{\underline{-10.8 V/V}}
 \end{aligned}$$

$$\begin{aligned}
 (d) \quad &\text{Using Miller's theorem to find } R_i: \\
 R_i &= \frac{47}{1 - \frac{V_o}{V_b}} = \frac{47}{1 + 10.8} = \underline{\underline{4K\Omega}}
 \end{aligned}$$

$$\begin{aligned}
 (e) \quad A_M &= \frac{V_o}{V_s} \cdot \frac{V_b}{V_b} = \frac{R_i}{R_s + R_i} \times \frac{V_o}{V_b} \\
 &= \frac{4K}{1K + 4K} \times -10.8 = \underline{\underline{-8.64}}
 \end{aligned}$$

$$\begin{aligned}
 (f) \quad C_{\pi} + C_{\mu} &= \frac{g_m}{2\pi f_T} = \frac{21.6 \times 10^{-3}}{2\pi \cdot 600 \times 10^6} \\
 &= 5.73 \text{ pF} \\
 C_{\pi} &= 5.73 - 0.8 = \underline{\underline{4.93 \text{ pF}}}
 \end{aligned}$$

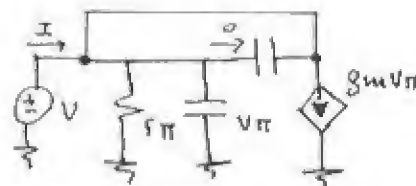
$$\begin{aligned}
 C_{in} &= C_{\pi} + C_{\mu} (1 + g_m R_i') \\
 &= 4.93 + 0.8 (1 + 21.6 \times (1 \parallel 1)) \\
 &= \underline{\underline{14.37 \text{ pF}}}
 \end{aligned}$$

$$(g) \quad f_H = \frac{1}{2\pi \cdot C_{in} \cdot R_{in}}$$

$$\begin{aligned}
 R_{in} &= R_i \parallel R_s = 4K \parallel 1K \\
 &= \underline{\underline{0.8K\Omega}}
 \end{aligned}$$

$$\begin{aligned}
 \Rightarrow f_H &= \frac{1}{2\pi \times 14.37 \times 10^{-12} \times 0.8 \times 10^3} \\
 f_H &= \underline{\underline{13.84 \text{ MHz}}}
 \end{aligned}$$

5.162



$$I = \frac{V}{r_{\pi}} + sC_{\pi} V_{\pi} + g_m V_{\pi}$$

$$Y_{in} = \left(g_m + \frac{1}{r_{\pi}} \right) + sC_{\pi}$$

$$Z_i = \frac{1}{\left(g_m + \frac{1}{r_{\pi}} \right) + sC_{\pi}}$$

$$= \frac{1}{\frac{1}{r_e} + sC_{\pi}} = \frac{r_e}{1 + sC_{\pi} r_e}$$

$$f_T = \frac{g_m}{2\pi (C_{\pi} + C_{\mu})}$$

Since C_{π} contains a component that is proportional to the bias current, it follows that at high currents $C_{\pi} \gg C_{\mu}$ and

$$f_T \approx \frac{g_m}{2\pi C_{\pi}} \approx \frac{1}{2\pi \cdot C_{\pi} r_e}$$

Thus,

$$Z_i = \frac{r_e}{1 + s/\omega_T} \quad (\text{at high currents})$$

The phase angle will be -45° at $\omega = \omega_T$, or

$$f = f_T = \underline{\underline{400 \text{ MHz}}}$$

CONT.

For a lower bias current so that $C_T = C_T$,

$$f_T = \frac{1}{4\pi C_T r_e}$$

$$\text{and } Z_i = \frac{r_e}{1 + \frac{s}{2\omega_T}}$$

-45° angle is obtained at $\omega = 2\omega_T$ or $f = 2f_T$
 $= 800 \text{ MHz}$

(Assuming f_T remains constant which is not necessarily true)

$$f_{CE} = 1 / 2\pi C_E R_{E'} \\ R_{E'} = R_E \parallel \left[\frac{r_{\pi} + r_x + (R_1 \parallel R_2 \parallel R_3)}{\beta_0 + 1} \right] \\ = 3.9 \parallel \left(\frac{10K + 50 + (33 \parallel 22 \parallel 5)K}{121} \right) \\ = 109.8 \Omega$$

$$C_E = 10 \mu F$$

$$\Rightarrow f_{CE} = \frac{1}{2\pi \times 10 \times 10^{-6} \times 109.8} \\ = 144.95 \text{ Hz}$$

$$f_L = \frac{\omega_L}{2\pi} = 14.87 + 15.55 + 109.8$$

$$f_L = 140.22 \text{ Hz}$$

5.163

Refer to Fig. P5.159 and Problem 5.159

$$\omega_L = \omega_{C1} + \omega_{C2} + \omega_{CE}$$

$$\omega_{C1} = \frac{1}{C_{C1} R_{C1}} \Rightarrow f_{C1} = \frac{1}{2\pi C_{C1} R_{C1}}$$

$$R_{C1} = R_S + [R_1 \parallel R_2 \parallel (r_x + r_{\pi})] \\ = 5K + [33K \parallel 22K \parallel (50 + 10K)] \\ = 10.7K\Omega$$

$$C_{C1} = 1 \mu F$$

$$\Rightarrow f_{C1} = \frac{1}{2\pi \cdot 1 \times 10^{-6} \times 10.7 \cdot 10^3} \\ = 14.87 \text{ Hz}$$

$$f_{C2} = 1 / 2\pi \cdot C_{C2} \cdot R_{C2}$$

$$R_{C2} = R_L + (R_C \parallel r_o) \\ = 5.6K + (4.7K \parallel 300K) \\ = 10.23K\Omega$$

$$C_{C2} = 1 \mu F$$

$$\Rightarrow f_{C2} = \frac{1}{2\pi \times 1 \cdot 10^{-6} \times 10.23 \cdot 10^3} \\ = 15.55 \text{ Hz}$$

5.164

Refer to Fig P5.159 and Problem 5.163.

To select C_E so that it contributes 90% of the value of ω_L :

$$\frac{1}{2\pi C_E R_{E'}} = 0.9 \times 100$$

$$R_{E'} = 109.8 \Omega \text{ (From problem 5.163)}$$

$$\Rightarrow C_E = \frac{1}{2\pi \cdot 109.8 \times 90} \\ = 16.1 \mu F //$$

To select C_1 so that it contributes 5% of f_L :

$$R_{C1} = 10.7K\Omega \text{ (From P 5.163)}$$

$$\Rightarrow C_1 = \frac{1}{2\pi \times 10.7 \cdot 10^3 \times 0.05 \times 100} \\ C_1 = 2.97 \mu F //$$

CONT.

To select C_2 so that it contributes to 5% of f_L :

$$R_{C2} = 10.23 \text{ k}\Omega \text{ (From P5.163)}$$

$$\Rightarrow C_2 = \frac{1}{2\pi \times 10.23 \cdot 10^3 \times 0.05 \times 100} = \underline{3.11 \mu\text{F}}$$

5.165

Refer to Fig. P5.159.

$$\begin{aligned} R_{C1} &= R_S + [R_B \parallel (r_x + r_{\pi})] \\ &= 10 + [10 \parallel (0.1 + 1)] \\ &= 10.99 \text{ k}\Omega \end{aligned}$$

$$\begin{aligned} R_{E'} &= R_E \parallel \frac{r_{\pi} + r_x + (R_B \parallel R_S)}{\beta + 1} \\ &\approx 1 \parallel \frac{1 + 0.1 + (10 \parallel 10)}{100 + 1} \\ &= 57 \Omega \end{aligned}$$

For C_E and C_{C1} to contribute equally to the determination of f_L ,

$$\begin{aligned} C_E R_{E'} &= C_{C1} R_{C1} \\ \Rightarrow \frac{C_E}{C_{C1}} &= \frac{R_{C1}}{R_{E'}} = \frac{10.99}{0.057} = \underline{193} \end{aligned}$$

5.166

Refer to Fig. P5.166.

(a) At midband frequencies

$$I_B = \frac{V_S}{R_S + r_{\pi}}$$

$$I_C = \beta \cdot I_B = \frac{\beta V_S}{R_S + r_{\pi}}$$

$$V_O = -I_C \cdot (R_C \parallel R_L)$$

$$= -\frac{\beta (R_C \parallel R_L) \cdot V_S}{R_S + r_{\pi}}$$

$$A_M = \frac{V_O}{V_S} = -\beta \frac{(R_C \parallel R_L)}{R_S + r_{\pi}}$$

(b) Pole due to C_E :

$$\omega_{PE} = \frac{1}{C_E (1 + \frac{R_S}{\beta + 1})} //$$

Pole due to C_{C1} :

$$\omega_{PC} = \frac{1}{C_{C1} (R_C + R_L)} //$$

Zeros are both at $s = 0$

$$\begin{aligned} (c) A(s) &= A_M \cdot \frac{s^2}{(s + \omega_{PE})(s + \omega_{PC})} \\ A(s) &= -\frac{\beta (R_C \parallel R_L)}{R_S + r_{\pi}} \cdot \frac{s^2}{\left[s + \frac{1}{C_E (1 + \frac{R_S}{\beta + 1})} \right] \left[s + \frac{1}{C_{C1} (R_C + R_L)} \right]} \end{aligned}$$

$$\begin{aligned} (d) A_M &= -\frac{100 (10 \parallel 10)}{10 + \frac{100}{40}} \\ &= \underline{-40 \text{ V/V}} \end{aligned}$$

(e) Since the resistance that forms the pole ω_{PE} is very small, we choose to make ω_{PE} the dominant pole, thus:

$$\begin{aligned} f_{PE} = f_L = 100 &= \frac{1}{2\pi C_E (25 + \frac{10 \text{ k}\Omega}{101})} \\ \Rightarrow C_E &= \frac{1}{2\pi \times 100 \times (0.025 + 0.100 \cdot 10^3)} \\ &= \underline{12.7 \mu\text{F}} \end{aligned}$$

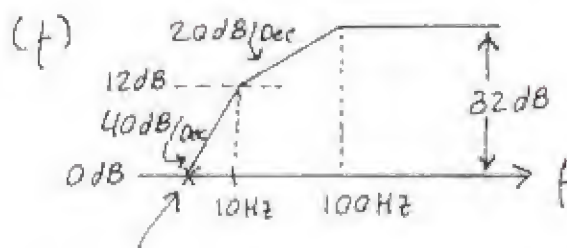
$$f_{PC} = 10 \text{ Hz} \Rightarrow$$

CONT.

$$10 \text{ Hz} = \frac{1}{2\pi C_C (R_L + R_C)}$$

$$\Rightarrow C_C = \frac{1}{2\pi \times 10 (10 + 10) \times 10^3}$$

$$= \underline{0.8 \mu\text{F}}$$



Unity-gain frequency must be an octave lower than 10 Hz.
i.e. at 5 Hz

$$(g) A(j\omega) = -A_M \frac{\omega^2}{(\omega_{PE} + j\omega)(\omega_{PC} + j\omega)}$$

$$= +40 \frac{\omega^2}{(\omega_{PE} + j\omega)(\omega_{PC} + j\omega)}$$

$$\text{Thus } \phi = \tan^{-1}\left(\frac{\omega}{\omega_{PE}}\right) - \tan^{-1}\left(\frac{\omega}{\omega_{PC}}\right)$$

$$= -\left[\tan^{-1}\frac{f}{f_{PE}} + \tan^{-1}\frac{f}{f_{PC}}\right]$$

$$= -\left[\tan^{-1}\frac{f}{100} + \tan^{-1}\frac{f}{10}\right]$$

Thus at $f = 100 \text{ Hz}$,

$$\phi = -[\tan^{-1} 1 + \tan^{-1} 10]$$

$$\approx -\underline{129.3^\circ}$$

5.167

Refer to Fig. P 5.167

$$(a) I_E = \frac{V_S}{r_e + R_E + \frac{1}{sC_E}}$$

$$I_C \approx I_E$$

$$V_O = -R_C I_C = \frac{-R_C}{r_e + R_E + \frac{1}{sC_E}} \cdot V_S$$

$$A(s) \equiv \frac{V_O}{V_S} = \frac{-R_C}{r_e + R_E + \frac{1}{sC_E}}$$

$$= \frac{-R_C}{r_e + R_E} \cdot \frac{s}{s + \frac{1}{C_E(r_e + R_E)}}$$

$$\text{Thus, } A_M = \frac{-R_C}{r_e + R_E}$$

$$\omega_L = \frac{1}{C_E(r_e + R_E)}$$

$$(b) A_M \text{ is reduced by the factor } \frac{r_e}{r_e + R_E}$$

$$= 1 + \frac{R_E}{r_e}$$

$$(c) \omega_L \text{ is reduced by the factor } \left(1 + \frac{R_E}{r_e}\right)$$

which is the same as the gain reduction factor. Thus, the value of R_E can be used as the parameter for exercising the gain-bandwidth trade off.

$$(d) R_E = 0:$$

$$|A_M| = \frac{R_C}{r_e} = \frac{10,000}{25} = \underline{400 \text{ V/V}}$$

$$f_L = \frac{1}{2\pi C_E r_e} = \frac{1}{2\pi \times 100 \times 10^{-6} \times 25}$$

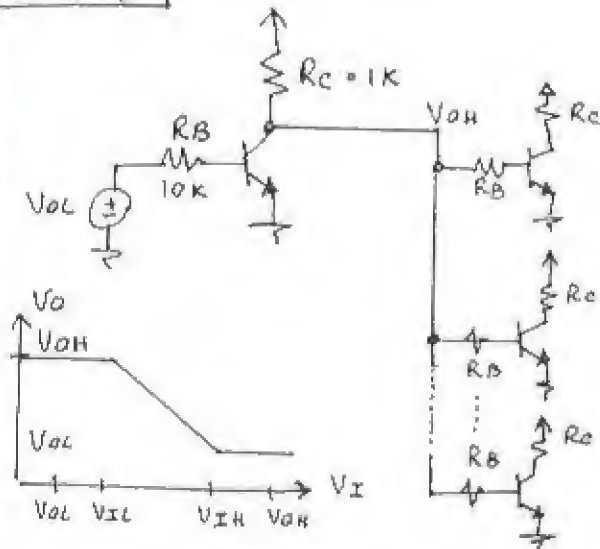
$$= \underline{63.7 \text{ Hz}}$$

To lower f_L by a factor of 5 use:

CONT.

$R_e = 4r_e = 100\Omega$. The gain is also lowered by a factor of 5 to 80 V/V

5.168



$$\begin{aligned} V_{IH} &= V_{BE} + I_B (E_{OS}) R_B \\ &= 0.7 + \left[\frac{(V_{CC} - V_{CESAT})}{R_C} \right] / 100 R_B \\ &= 0.7 + \frac{5 - 0.2 \times 10}{100} \\ &= 1.18V \end{aligned}$$

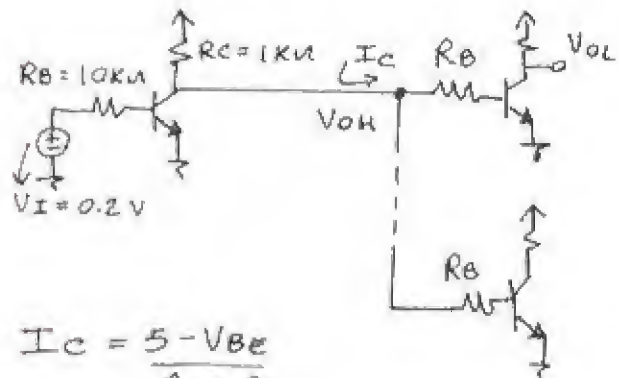
For $NMH = V_{OH} - V_{IH} = 1$
 $V_{OH} = 1 + 1.18 = 2.18V$

$V_{OH} = V_{CC} - R_C \cdot \frac{V_{CC} - V_{BE}}{R_C + \frac{R_B}{N}}$
 $= 5 - 1 \left(\frac{5 - 0.7}{1 + \frac{10}{N}} \right) > 2.18$

$N < 19.05 \Rightarrow N = \underline{19}$

5.169

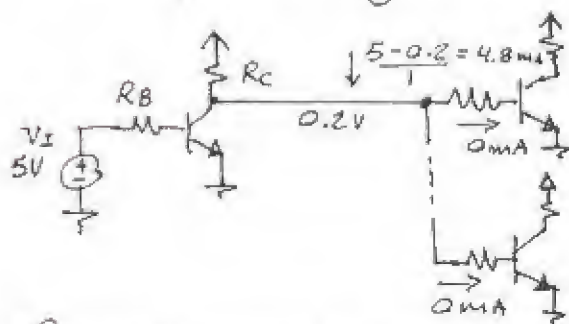
(a) Input is low:



$$\begin{aligned} I_C &= \frac{5 - V_{BE}}{R_C + \frac{R_B}{10}} \\ &= \frac{5 - 0.7}{1 + 10/10} = \underline{2.15mA} \end{aligned}$$

$PD_{V_I \text{ Low}} = I_C^2 \cdot R_C = 2.15^2 \times 1$
 $= \underline{4.62mW}$

(b) Input is high:

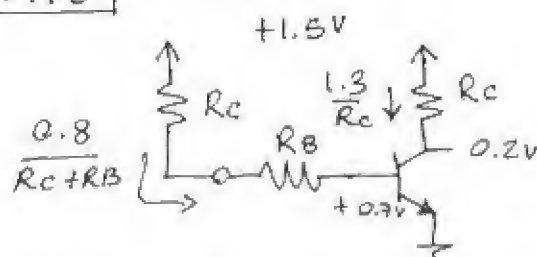


Power dissipated neglecting the base circuit

$PD_{V_I \text{ High}} = V_{CC} I_C$
 $= 5 \times 4.8 = \underline{24mW}$

(c) $PD_{AVG} = \frac{1}{2} (4.62 + 24)$
 $= \underline{14.31mW}$

5.170



$$\beta_{\text{forced}} = 10 = \frac{1.3/R_c}{0.8/(R_c + R_B)} \quad (1)$$

$$\frac{80}{13} = \frac{R_c + R_B}{R_c} = 1 + \frac{R_B}{R_c}$$

$$\frac{R_B}{R_c} = \frac{67}{13} \Rightarrow R_B = 5.15 R_c \quad (2)$$

Total current from supply

$$= \frac{1.3}{R_c} + \frac{0.8}{R_c + R_B}$$

From Equ. (1) $\frac{0.8}{R_c + R_B} = \frac{1.3/R_c}{10}$

$$\text{Thus } I_{\text{TOTAL}} = \frac{1.3}{R_c} + \frac{1}{10} \frac{1.3}{R_c}$$

$$= \frac{1.1 \times 1.3}{R_c}$$

$$P_{D\text{TOTAL}} = I_{\text{TOTAL}} \times 1.5V$$

$$= \frac{1.1 \times 1.3 \times 1.5}{R_c} = 1 \text{ mW}$$

$$R_c = \frac{1.1 \times 1.3 \times 1.5}{1} = 2.145 \text{ k}\Omega$$

Choose $R_c = 2.2 \text{ k}\Omega$

$$R_B = 5.15 \times 2.145 = 11 \text{ k}\Omega$$

5.171

Refer to Fig. P5.171

V_x	V_y	V_z
0.2	0.2	5
0.2	5	0.2
5	0.2	0.2
5	5	0.2

These are 4 input combinations. When any input is high, (V_x and/or V_y) high, $V_z = 0.2V$

When both inputs are low, (V_x and V_y) low V_z is high

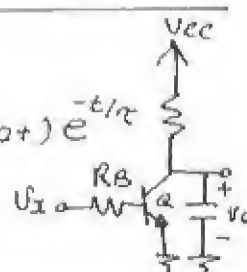
5.172

$$V_o(t) = V_{\infty} - (V_{\infty} - V_{o+}) e^{-t/\tau}$$

$$V_{\infty} = V_{CC}$$

$$V_{o+} = V_{CEsat}$$

$$\tau = C \cdot R_c$$



Thus,

$$V_o(t) = V_{CC} - (V_{CC} - V_{CEsat}) e^{-t/\tau_{RC}}$$

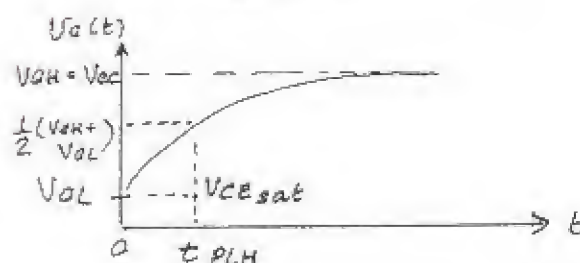
$$V_o(t) = 5 - (5 - 0.2) e^{-t/(10 \times 10^{-12} \times 1 \times 10^3)}$$

$$\frac{1}{2} (V_{OH} + V_{OL}) = 2.6V$$

$$2.6 = 5 - 4.8 e^{-\frac{t_{PLH}}{10^{-8}}}$$

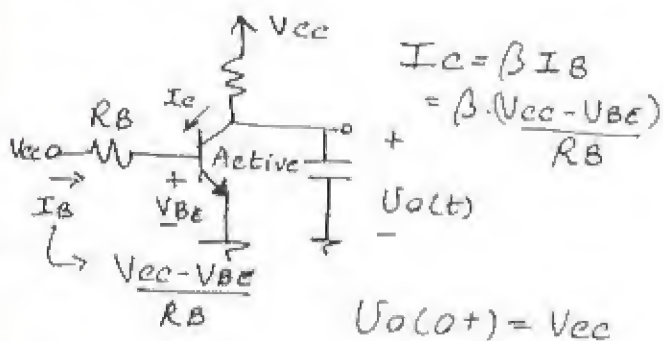
$$t_{PLH} = 0.69 \times 10^{-8} \text{ s.}$$

$$t_{PLH} = 6.9 \text{ ns}$$

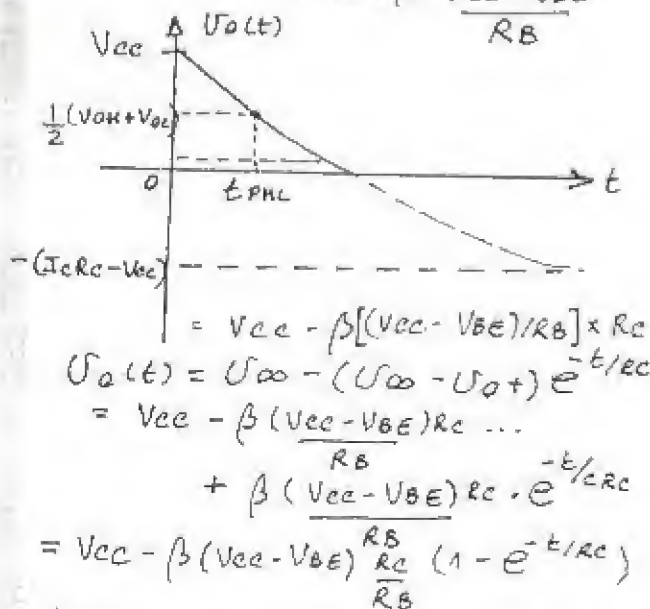
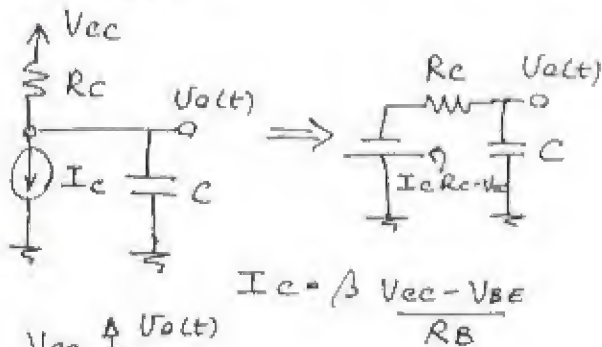


5.173

At $t = 0^+$



Thus the equivalent circuit for the capacitor discharge will be:



At $t = t_{PHL}$, $V_O = \frac{1}{2} (V_{OH} + V_{OL})$
 $= \frac{1}{2} (V_{CC} + V_{CE_{sat}})$

$= \frac{1}{2} (5 + 0.2) = 2.6V$

Thus,

$2.6 = 5 - 50 (5 - 0.7) \frac{1}{10} (1 - e^{-\frac{t_{PHL}}{RC}})$

$1 - e^{-\frac{t_{PHL}}{RC}} = \frac{0.48}{4.3}$

$t_{PHL} = 0.118 \times 10 \times 10^{-12} \times 1 \times 10^3$
 $= \underline{1.18 ns}$

Comparing this value to that of t_{PLH} found in Problem 5.172 we observe that t_{PHL} is much smaller than t_{PLH} .

$t_p = \frac{1}{2} (t_{PLH} + t_{PHL})$

$= \frac{1}{2} (6.9 + 1.18) = \underline{4 ns}$

Chapter 6 - Problems

6.1

Assume $0.18\mu\text{m}$ CMOS process and refer to Table 6.1:

$\mu_n C_{ox} = 387 \mu\text{A/V}^2$ Also assume $\frac{W}{L} = 10$

Assuming operation in saturation mode:

$$V_{ov} = 0.15\text{V} \Rightarrow I_D = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} V_{ov}^2 = \frac{1}{2} \times 387 \times 0.15^2 \times 10$$

$$I_D = 43.5 \mu\text{A}$$

$$V_{ov} = 0.4\text{V} \Rightarrow I_D = 309.6 \mu\text{A}$$

Therefore:

$$0.15\text{V} \leq V_{ov} \leq 0.4\text{V} \Rightarrow 43.5 \mu\text{A} \leq I_D \leq 309.6 \mu\text{A}$$

Now if we consider the same range of current for I_C of a BJT and we assume an npn transistor in a standard high-voltage process: (refer to Table 6.2)

$$I_S = 5 \times 10^{-15} \text{A} = 5 \times 10^{-9} \mu\text{A}$$

$$I_C = I_S e^{V_{BE}/V_T} \Rightarrow V_{BE} = V_T \ln \frac{I_C}{I_S}$$

$$I_C = 43.5 \mu\text{A} \Rightarrow V_{BE} = 0.025 \ln \frac{43.5}{5 \times 10^{-9}} = 0.572\text{V}$$

$$I_C = 309.6 \mu\text{A} \Rightarrow V_{BE} = 0.621\text{V}$$

Therefore:

$$43.5 \mu\text{A} \leq I_C \leq 309.6 \mu\text{A} \Rightarrow 0.572\text{V} \leq V_{BE} \leq 0.621\text{V}$$

6.2

If the area of the emitter-base junction is changed by a factor of 10, then I_S is changed by the same factor. If V_{BE} is kept constant, then I_C is also changed by the same factor:

$$I_C = I_S e^{V_{BE}/V_T} \quad I_S \propto A, I_C \propto I_S \Rightarrow I_C \propto A$$

$$A_2 = 10A_1 \Rightarrow I_{C2} = 10I_{C1}$$

If I_C is kept constant, then V_{BE} changes:

$$I_{S2} = 10I_{S1} \Rightarrow I_S e^{V_{BE2}/V_T} = 10I_S e^{V_{BE1}/V_T}$$

$$e^{\frac{V_{BE2} - V_{BE1}}{V_T}} = 10 \Rightarrow V_{BE2} - V_{BE1} = V_T \ln 10 = 0.058\text{V}$$

or 58mV

6-3

$$\frac{W}{L} = 10, I_D = 100 \mu\text{A}, I_D = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} V_{ov}^2$$

	0.8 μm		0.5 μm		0.25 μm		0.18 μm	
	NMOS	PMOS	NMOS	PMOS	NMOS	PMOS	NMOS	PMOS
$V_{ov}^{(1)}$	0.4	-0.59	0.32	-0.54	0.27	-0.46	0.23	-0.41
$V_{GS}^{(1)}$	1.1	-1.29	1.02	-1.34	0.7	-1.08	0.71	-0.9

$$V_{ov} = \sqrt{\frac{2I_D}{\mu_n C_{ox} \frac{W}{L}}} = \sqrt{\frac{2 \times 100}{387 \times 10}} = \sqrt{\frac{20}{387}}$$

$$V_{GS} = V_{ov} + V_{th}$$

6.4

$$|V_{ov}| = 0.25\text{V}, I_D = 100 \mu\text{A}$$

$$I_D = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} V_{ov}^2 \Rightarrow \frac{W}{L} = \frac{2I_D}{\mu_n C_{ox} V_{ov}^2}$$

For NMOS:

$$K_n = 267 \frac{\mu\text{A}}{\text{V}^2} \Rightarrow \left(\frac{W}{L}\right)_n = \frac{2 \times 100}{267 \times 0.25^2} = 11.98$$

For PMOS:

$$K_p = 93 \frac{\mu\text{A}}{\text{V}^2} \Rightarrow \left(\frac{W}{L}\right)_p = \frac{2 \times 100}{93 \times 0.25^2} = 34.4$$

6.5

$$i_{on} = i_{op} \Rightarrow \frac{1}{2} \mu_n C_{ox} \left(\frac{W}{L}\right)_n V_{on}^2 = \frac{1}{2} \mu_p C_{ox} \left(\frac{W}{L}\right)_p V_{op}^2$$

We also have $g_{m1} = g_{m2}$

$$g_m = \frac{2I_D}{V_{ov}} = \mu_n C_{ox} \left(\frac{W}{L}\right)_n V_{on} = \mu_p C_{ox} \left(\frac{W}{L}\right)_p V_{op} \quad (2)$$

$$(1), (2) \Rightarrow \left(\frac{W}{L}\right)_p = \frac{\mu_n}{\mu_p} = \frac{460}{160} = 2.88$$

6.6

$$g_m = 10 \text{ mA/V}, V_{ov} = 0.2\text{V}$$

$$g_m = \frac{2I_D}{V_{ov}} \Rightarrow I_D = \frac{g_m V_{ov}}{2} = \frac{10 \times 0.2}{2} = 1 \text{ mA}$$

$$I_D = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} V_{ov}^2 \Rightarrow \frac{W}{L} = \frac{2I_D}{\mu_n C_{ox} V_{ov}^2} = \frac{2 \times 1 \times 10^3}{387 \times 0.2^2} = 129$$

$$\text{for an npn transistor: } g_{m1} = \frac{I_C}{V_T} \Rightarrow I_C = 10 \times 0.025 = 0.25$$

6.7

$$\frac{W}{L} = 10 \quad I_D = 100 \mu A$$

	0.8 μm	0.5 μm	0.25 μm	0.18 μm
	NMOS	PMOS	NMOS	PMOS
g_m (mA/V)	0.5	0.34	0.62	0.37
	0.73	0.43	0.88	0.41

$$g_m = \sqrt{\frac{2\mu_n C_{ox}}{L} \frac{W}{L} I_D} = \sqrt{\frac{2\mu_n C_{ox}}{L} \frac{W}{L} I_D} = 44.7 \sqrt{\frac{\mu_n C_{ox}}{L} \frac{W}{L} \frac{I_D}{V}}$$

6.11

$$L = 0.3 \mu m, I_D = 100 \mu A, V_{OV} = 0.2 V$$

$$g_m = \frac{2I_D}{V_{OV}} = \frac{2 \times 100 \mu A}{0.2} = 1 \text{ mA/V}$$

$$r_o = \frac{V_A}{I_D} = \frac{V_A L}{I_D} = \frac{5 \times 0.3}{0.1} = 15 \text{ k}\Omega$$

$$A_o = g_m r_o = 1 \times 15 = 15 \text{ V/V}$$

$$g_m = \mu_n C_{ox} \frac{W}{L} V_{OV} \Rightarrow W = \frac{g_m L}{\mu_n C_{ox} V_{OV}} = \frac{1 \times 0.3}{387 \times 10^3 \times 0.2}$$

$$W = 3.88 \mu m$$

6.8

$$V_{OV} = 0.25 V$$

For an npn transistor: $g_m = \frac{I_C}{V_T} = \frac{0.1}{0.025} = 4 \text{ mA/V}$

For an NMOS with the same g_m , i.e. $g_m = 4 \text{ mA/V}$

we will have: $g_m = \frac{2I_D}{V_{OV}} \Rightarrow I_D = g_m \times \frac{V_{OV}}{2} = 0.5 \text{ mA}$

$$I_D = 0.5 \text{ mA}$$

6.9

Assuming large r_o for both transistors, for

case (a) we have $r = \frac{1}{g_m} = \frac{1}{\sqrt{\frac{2\mu_n C_{ox}}{L} \frac{W}{L} I_D}}$

$$r = \frac{10^3}{\sqrt{2 \times 200 \times 10 \times 0.1 \times 10^{-3}}} = 1.58 \text{ k}\Omega$$

For case (b) we have $r = r_{\pi} \parallel \frac{1}{g_m} = \frac{\beta}{(\beta+1)g_m}$

$$r = \frac{\beta V_T}{(\beta+1)I_C} = \frac{V_T}{I_C} = \frac{0.025}{0.1} = 0.25 \text{ k}\Omega$$

$$r = 250 \Omega$$

6.10

$$g_m = \frac{2I_D}{V_{OV}} = \frac{2 \times 100 \mu A}{0.5} = 0.4 \text{ mA/V}$$

$$r_o = \frac{V_A}{I_D} = \frac{V_A L}{I_D} = \frac{25 \times 1}{0.1} = 250 \text{ k}\Omega$$

$$A_o = g_m r_o = 0.4 \times 250 = 100 \text{ V/V}$$

$$g_m = \mu_n C_{ox} \frac{W}{L} V_{OV} \Rightarrow W = \frac{g_m L}{\mu_n C_{ox} V_{OV}} = \frac{0.4 \times 1}{127 \times 10^3 \times 0.5}$$

$$W = 6.3 \mu m$$

6.12

$$\text{BJT: } \beta = 100, V_A = 100 V$$

$$\text{MOSFET: } \mu_n C_{ox} = 200 \mu A/V^2, \frac{W}{L} = 40, V_A = 10 V$$

Device	BJT		MOSFET	
Bias current (mA)	0.1	1	0.1	1
g_m (mA/V)	4	40	1.26	4
r_o (k Ω)	1000	100	100	10
A_o (V/V)	4000	4000	126	40
R_i (k Ω)	25	2.5	∞	∞

$$R_i = r_{\pi} = \beta/g_m \text{ For BJT}$$

6.13

$$L = 0.3 \mu m, W = 6 \mu m, V_{OV} = 0.2 V$$

$$I_D = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} V_{OV}^2 = \frac{1}{2} \times 387 \times \frac{6}{0.3} \times 0.2^2 = 155 \mu A$$

$$I_D = 0.155 \text{ mA}$$

$$g_m = \frac{2I_D}{V_{OV}} = 1.55 \text{ mA/V}$$

$$C_{gs} = \frac{2}{3} \frac{W}{L} C_{ox} + C_{ov} = \frac{2}{3} W L C_{ox} + W L_{ov} C_{ox}$$

$$C_{gs} = \frac{2}{3} \times 6 \times 0.3 \times 8.6 + 6 \times 0.37 = 12.54 \text{ fF}$$

$$C_{gd} = C_{ov} W = 0.37 \times 6 = 2.22 \text{ fF}$$

$$f_T = \frac{g_m}{2\pi(C_{gs} + C_{gd})} = \frac{1.55 \times 10^{-3}}{2\pi(12.54 + 2.22) \times 10^{-15}} = 16.7 \text{ GHz}$$

If we use the approximation formula:

$$f_T \approx \frac{1.5 \mu_n V_{OV}}{2\pi L^2} \text{ when } C_{gs} \gg C_{gd}, C_{gs} \approx \frac{2}{3} W L C_{ox}$$

$$f_T \approx \frac{1.5 \times 450 \times 10^4 \times 0.2}{2\pi \times 0.3^2 \times 10^{12}} = 23.9 \text{ GHz}$$

The approximation formula overestimates

(Cont.)

f_T because it ignores $W L_{ov} C_{ox}$ or C_{ov} in C_{gs} and C_{gd} calculation.

6.14

$$L = 0.3 \mu\text{m} \quad W = 6 \mu\text{m} \quad V_{OV} = 0.2 \quad C_L = 100 \text{ fF}$$

$$A_0 = \frac{2V_{AL}}{V_{OV}} = \frac{2 \times 5 \times 0.3}{0.2} = 15 V/V$$

$$I_D = \frac{1}{2} K_n' \frac{W}{L} \frac{V_{OV}^2}{0.3} = \frac{1}{2} \times 387 \times \frac{6}{0.3} \times 0.2^2 = 0.155 \text{ mA}$$

$$r_D = \frac{V_{AL}}{I_D} = \frac{5 \times 0.3}{0.155} = 9.3 \text{ k}\Omega$$

$$f_p = \frac{1}{2\pi C_L r_D} = \frac{1}{2\pi \times 100 \times 10^{-12} \times 9.3 \times 10^3} = 164.2 \text{ MHz}$$

$$g_m = \frac{2I_D}{V_{OV}} = 1.55 \text{ mA/V}$$

$$f_T = \frac{g_m}{2\pi C_L} = 2.5 \text{ GHz}$$

In order to double f_T or equivalently double g_m , $\sqrt{I_D}$ has to be doubled or I_D has to be multiplied by 4: $g_m = \sqrt{2K_n' \frac{W}{L} I_D}$, $f_T \propto g_m \propto \sqrt{I_D}$

$$I_D = 4 \times 0.155 = 0.62 \text{ mA}$$

$$\text{In that case, } A_0 \propto \frac{1}{V_{OV}} \propto \frac{1}{\sqrt{I_D}} \Rightarrow A_0 = 15 \times \frac{1}{2} = 7.5 V/V$$

$$f_p \propto \frac{1}{r_D} \propto I_D \Rightarrow f_p = 164.2 \times 4 = 656.8 \text{ MHz}$$

6.15

$I_C = 10 \mu\text{A}$, High-voltage process:

$$g_m = \frac{I_C}{V_T} = \frac{10 \times 10^{-3}}{0.025} = 0.4 \text{ mA/V}$$

$$C_{de} = C_F g_m = 0.35 \times 10^{-9} \times 0.4 \times 10^{-3} = 140 \times 10^{-15} \text{ F} = 140 \text{ fF}$$

$$C_{je} = 2 C_{jco} = 2 \times 1 = 2 \text{ pF} = 2000 \text{ fF}$$

$$C_{\pi} = C_{de} + C_{je} = 2140 \text{ fF}$$

$$C_{\mu} \ll C_{\mu 0} = 0.3 \text{ pF} = 300 \text{ fF}$$

$$f_T = \frac{g_m}{2\pi(C_{\pi} + C_{\mu})} = \frac{0.4 \times 10^{-3}}{2\pi(2140 + 300) \times 10^{-15}} = 26.1 \text{ MHz}$$

$I_C = 100 \mu\text{A}$, High-voltage process:

$$g_m = 10 \times 0.4 = 4 \text{ mA/V}, \quad C_{de} = 10 \times 140 = 1400 \text{ fF}$$

$$C_{\pi} = 3400 \text{ fF} \Rightarrow f_T = \frac{4 \times 10^{-3}}{2\pi(3400 + 300) \times 10^{-15}} = 172.1 \text{ MHz}$$

$I_C = 10 \mu\text{A}$, Low-voltage process

$$g_m = \frac{10 \times 10^{-3}}{0.025} = 0.4 \text{ mA/V}$$

$$C_{de} = 10 \times 10^{-12} \times 0.4 \times 10^{-3} = 4 \text{ fF}$$

$$C_{je} = 2 \times 5 \text{ fF} = 10 \text{ fF}$$

$$C_{\pi} = C_{de} + C_{je} = 14 \text{ fF}$$

$$C_{\mu} \ll C_{\mu 0} = 5 \text{ fF}$$

$$f_T = \frac{g_m}{2\pi(C_{\pi} + C_{\mu})} = \frac{0.4 \times 10^{-3}}{2\pi(14 + 5) \times 10^{-15}} = 3.35 \text{ GHz}$$

$I_C = 100 \mu\text{A}$, Low-voltage process

$$g_m = \frac{100 \times 10^{-3}}{0.025} = 4 \text{ mA/V}$$

$$C_{de} = 10 \times 4 = 40 \text{ fF}$$

$$C_{\pi} = 40 + 10 = 50 \text{ fF}, \quad C_{\mu} = 5 \text{ fF}$$

$$f_T = \frac{4 \times 10^{-3}}{2\pi(50 + 5) \times 10^{-15}} = 11.6 \text{ GHz}$$

In Summary:

	Standard High-Voltage npn		Standard Low-Voltage npn	
	$I_C = 10 \mu\text{A}$	$I_C = 100 \mu\text{A}$	$I_C = 10 \mu\text{A}$	$I_C = 100 \mu\text{A}$
f_T	26.1 MHz	172.1 MHz	3.35 GHz	11.6 GHz

6.16

$L = 1 \mu\text{m}$, $I_D = 100 \mu\text{A}$, $0.8 \mu\text{m}$ - NMOS

a) $V_{OV} = 0.25 \text{ V}$

$$I_D = \frac{1}{2} K_n' \frac{W}{L} \frac{V_{OV}^2}{0.1} \Rightarrow W = \frac{2L I_D}{K_n' C_{ox} V_{OV}^2} = \frac{2 \times 1 \times 100}{12.7 \times 0.25^2} \Rightarrow W = 25.2 \mu\text{m}$$

$$g_m = \frac{2I_D}{V_{OV}} = \frac{2 \times 100 \times 10^{-3}}{0.25} = 0.8 \text{ mA/V}$$

$$r_D = \frac{V_{AL}}{I_D} = \frac{25 \times 1}{0.1} = 25 \text{ k}\Omega$$

$$A_0 = g_m r_D = 20 V/V$$

$$C_{gs} = \frac{2}{3} W L C_{ox} + W L_{ov} C_{ox} = \frac{2}{3} \times 25.2 \times 1 \times 2.3 + 25.2 \times 0.1$$

$$C_{gs} = 43.68 \text{ fF} \approx 44 \text{ fF}$$

$$C_{gd} = W L_{ov} C_{ox} = 25.2 \times 0.2 = 5.04 \text{ fF}$$

$$f_T = \frac{g_m}{2\pi(C_{gs} + C_{gd})} = \frac{0.8 \times 10^{-3}}{2\pi(44 + 5.04) \times 10^{-15}} = 2.6 \text{ GHz}$$

b) $f_T \propto g_m \propto V_{OV}$ therefore in order to double f_T ,

V_{OV} has to be doubled: $V_{OV} = 0.5 \text{ V}$. Consequently,

$$W = 25.2 / 4 = 6.3 \mu\text{m} \quad r_D, C_{gs}, C_{gd} \text{ unchanged}$$

$$g_m = \frac{0.8}{2} = 0.4 \text{ mA/V}, \quad A_0 = \frac{20}{2} = 10 V/V$$

6.17

$$I_C = 1 \text{ mA} \Rightarrow g_m = \frac{I_C}{V_T} = 40 \text{ mA/V}$$

For pnp:

$$C_{de} = \tau_F g_m = 30 \times 40 = 1200 \text{ pF}$$

$$C_{je} = 2C_{j0} = 2 \times 0.3 = 0.6 \text{ pF}$$

$$C_{\pi} = 1200.6 \text{ pF}$$

$$C_{\mu} \approx 1 \text{ pF}$$

$$\Rightarrow f_T = \frac{g_m}{2\pi(C_{\pi} + C_{\mu})} = \frac{40}{2\pi(1200.6 + 1)} \text{ MHz}$$

$$f_T = 5.3 \text{ MHz}$$

For npn:

$$C_{de} = \tau_F g_m = 0.35 \times 40 = 14 \text{ pF}$$

$$C_{je} = 2 \times 1 = 2 \text{ pF}$$

$$C_{\mu} \approx 0.3 \text{ pF}$$

$$C_{\pi} = 14 + 2 = 16 \text{ pF} \Rightarrow f_T = \frac{40}{2\pi(16 + 0.3)} = 391 \text{ MHz}$$

6.18

$$A_0 = g_m r_o = \frac{2I_D}{V_{ov}} \times \frac{V_A}{I_D} = \frac{2V_A}{V_{ov}} = \frac{2V_A L}{V_{ov}}$$

Therefore A_0 is only determined by setting values for L and V_{ov} .

$$f_T = \frac{g_m}{2\pi(C_{gs} + C_{gd})} = \frac{2I_D/V_{ov}}{2\pi(\frac{2}{3}WL C_{ox} + C_{ov} + C_{ov})}$$

If we assume that C_{ov} is very small or equivalently

$$C_{gs} \gg C_{gd} \text{ and } C_{gs} = \frac{2}{3}WL C_{ox}$$

(replace I_D with $\frac{1}{2}K_n \frac{W}{L} V_{ov}^2$)

$$f_T \approx \frac{K_n \frac{W}{L} V_{ov}}{2\pi \times \frac{2}{3}WL C_{ox}} = \frac{3}{4\pi} \frac{V_{ov}}{L} = \frac{3}{4\pi} \mu_n \frac{V_{ov}}{L^2}$$

As we can see f_T can be determined after knowing V_{ov} and L , it is not dependent on either I_D or W .

6.19

$$V_{ov} = 0.2 \text{ V}, L = 0.2 \mu\text{m}, 0.3 \mu\text{m}, 0.4 \mu\text{m}$$

$$A_0 = g_m r_o = \frac{2V_A}{V_{ov}} = \frac{2V_A L}{V_{ov}} = \frac{2 \times 5 \times L}{0.2} = 50L \text{ V/V}$$

$$f_T \approx \frac{1.5 \mu_n V_{ov}}{2\pi L^2} = \frac{1.5 \times 450 \times 10^4 \times 0.2}{2 \times 3.14 \times L^2 \times 10^{-12}} = \frac{2.15}{L^2} \text{ GHz}$$

$L (\mu\text{m})$	0.2	0.3	0.4
$A_0 (\text{V/V})$	10	15	20
$f_T (\text{GHz})$	53.75	23.9	13.4

6.20

$$L = 0.5 \mu\text{m}, V_{ov} = 0.3 \text{ V}, C_L = 1 \text{ pF}, f_T = 100 \text{ MHz}$$

$$f_T = \frac{g_m}{2\pi C_L} \Rightarrow g_m = 2\pi C_L f_T = 2\pi \times 1 \times 10^8 = 628 \text{ mA/V}$$

$$g_m = \frac{2I_D}{V_{ov}} \Rightarrow I_D = g_m \times V_{ov} / 2 = 628 \times 0.3 / 2$$

$$I_D = 94.2 \text{ } \mu\text{A}$$

$$I_D = \frac{1}{2} K_n' \frac{W}{L} V_{ov}^2 \Rightarrow W = \frac{2I_D}{K_n' V_{ov}^2} = \frac{2 \times 94.2 \times 10^{-6}}{150 \times 0.3^2} = 5.51 \mu\text{m}$$

$$W = 5.51 \mu\text{m}$$

$$r_o = \frac{V_A}{I_D} = \frac{V_A L}{I_D} = \frac{20 \times 0.5}{94.2 \times 10^{-6}} = 106.2 \text{ k}\Omega$$

$$A_0 = g_m r_o = \frac{628 \times 106.2}{1000} = 66.7 \text{ V/V}$$

$$f_{3dB} = \frac{1}{2\pi C_L r_o} = \frac{1}{2\pi \times 1 \times 106.2 \times 10^3} = 1.5 \text{ MHz}$$

6.21

$$I_D = I_{REF} = 50 \mu\text{A}, L = 0.5 \mu\text{m}, W = 5 \mu\text{m}, V_E = 0.5 \text{ V}$$

$$I_D = I_D = \frac{1}{2} K_n' \frac{W}{L} V_{ov}^2 \quad K_n' = 250 \mu\text{A/V}^2$$

$$50 = \frac{1}{2} \times 250 \times \frac{5}{0.5} (V_{GS} - 0.5)^2 \Rightarrow V_{GS} = 0.7 \text{ V}, 0.3 \text{ V}$$

$V_{GS} = 0.3 \text{ V} < V_E$ is not acceptable, therefore

$$V_{GS} = 0.7 \text{ V}$$

$$I_D = I_{REF} = \frac{V_{DD} - V_{GS}}{R} \Rightarrow \frac{1.8 - 0.7}{R} = 0.050 \Rightarrow R = 22 \text{ k}\Omega$$

Q_1 and Q_2 have the same V_{GS} . The lowest value

of V_D or V_{DS2} is when $V_{DS} = V_{GS} - V_E = 0.7 - 0.5 = 0.2 \text{ V}$

hence $V_{Dmin} = 0.2 \text{ V}$

$$r_o = \frac{V_A}{I_D} = \frac{V_A L}{I_D} = \frac{20 \times 0.5}{0.05} = 200 \text{ k}\Omega$$

$$\Delta I_D = \frac{\Delta V_D}{r_o} = \frac{1}{200 \text{ k}} = 5 \mu\text{A} \Rightarrow \Delta I_D = 5 \mu\text{A}$$

6.22

$$\mu_n C_{ox} = 250 \mu\text{A}/\text{V}^2, V_A = 20 \text{ V}/\mu\text{m}, V_E = 0.6 \text{ V}$$

$$\frac{\Delta I_D}{I_D} = 5\% \Rightarrow \Delta I_D = 5 \mu\text{A} \quad \text{For } \Delta V_G = 1.8 - 0.25 = 1.55 \text{ V}$$

$$r_D = \frac{\Delta V_G}{\Delta I_D} = \frac{1.55}{5 \mu\text{A}} = 310 \text{ k}\Omega$$

$$r_D = \frac{V_A L}{I_D} \Rightarrow L = I_D \frac{r_D}{V_A} = 0.1 \times \frac{310}{20} = 1.55 \mu\text{m}$$

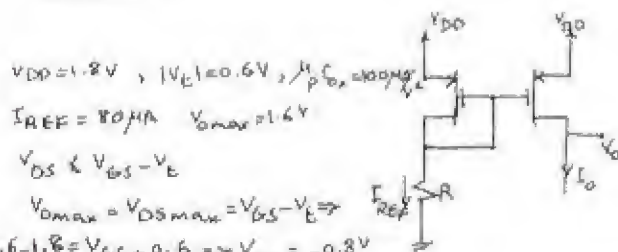
$$V_{Dmin} = V_{GS} - V_E = 0.25 \Rightarrow V_{GS} = 0.25 + 0.6 = 0.85 \text{ V}$$

$$R = \frac{V_{DD} - V_{GS}}{I_D} = \frac{1.8 - 0.85}{0.1} = 9.5 \text{ k}\Omega$$

$$I_D = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_E)^2 \Rightarrow W = \frac{2 L I_D}{\mu_n C_{ox} (V_{GS} - V_E)^2}$$

$$\Rightarrow W = \frac{2 \times 1.55 \times 100}{250 (0.85 - 0.6)^2} = 19.84 \mu\text{m}$$

6.23



$$V_{DD} = 1.8 \text{ V}, |V_E| = 0.6 \text{ V}, \mu_p C_{ox} = 100 \mu\text{A}/\text{V}^2$$

$$I_{REF} = 80 \mu\text{A}, V_{Dmax} = 1.6 \text{ V}$$

$$V_{DS} \leq V_{GS} - V_E$$

$$V_{Dmax} = V_{DSmax} = V_{GS} - V_E \Rightarrow$$

$$1.6 - 1.8 = V_{GS} + 0.6 \Rightarrow V_{GS} = -0.8 \text{ V}$$

$$\Rightarrow V_G = 1.8 - 0.8 = 1 \text{ V}$$

$$R = \frac{V_G}{I_D} = \frac{1}{0.080} = 12.5 \text{ k}\Omega$$

$$I_D = \frac{1}{2} \mu_p C_{ox} (V_{GS} - V_E)^2 \frac{W}{L} \Rightarrow W = \frac{2 L I_D}{\mu_p C_{ox} (V_{GS} - V_E)^2}$$

$$\frac{W}{L} = \frac{2 \times 80}{100 (-0.8 + 0.6)^2} = 40$$

6.24

$$W_2 = 4W_1, L_1 = L_2, V_{OV} = 0.3 \text{ V}, I_{REF} = 20 \mu\text{A}$$

$$I_D = I_{REF} \frac{(W/L)_2}{(W/L)_1} = 20 \times 4 = 80 \mu\text{A}$$

$$V_{Dmin} = V_{OV} = 0.3 \text{ V}$$

$$V_E = 0.5 \text{ V} \quad \text{According to Eq. 6.11 } I = \frac{(W/L)_2}{(W/L)_1} I_{REF} \left(\frac{1 + V_{D1} - V_{GS}}{V_{A2}} \right)$$

$$V_{OV} = V_{GS} - V_E \Rightarrow V_{GS} = 0.3 + 0.5 = 0.8 \text{ V}$$

$$1 + \frac{V_D - V_{GS}}{25} = 1 \Rightarrow V_D = 0.8 \text{ V}$$

$$\text{or we could simply say } V_{DS1} = V_{DS2} = V_D \text{ and}$$

$$\text{Since } V_{DS1} = V_{GS1} = 0.8 \text{ V} \Rightarrow V_D = 0.8 \text{ V}$$

$$r_{D2} = \frac{V_A}{I_{D2}} = \frac{25}{0.08} = 312.5 \text{ k}\Omega$$

$$r_{D2} = \frac{\Delta V_D}{\Delta I_D} = \frac{1}{\Delta I_D} \Rightarrow \Delta I_D = \frac{1}{312.5 \text{ k}} = 3.2 \mu\text{A}$$

6.25

Refer to Fig. P6.25

$$V_{GS1} = V_{GS2} \Rightarrow \frac{I_{D2}}{I_{D1}} = \frac{(W/L)_2}{(W/L)_1} \Rightarrow I_{D2} = I_{REF} \frac{(W/L)_2}{(W/L)_1}$$

$$I_{D2} = I_{D3}$$

$$V_{GS3} = V_{GS4} \Rightarrow \frac{I_{D3}}{I_{D4}} = \frac{(W/L)_3}{(W/L)_4} \Rightarrow \frac{I_{D2}}{I_{D4}} = \frac{(W/L)_3}{(W/L)_4}$$

$$I_{D4} = I_{REF} \frac{(W/L)_2}{(W/L)_1} \frac{(W/L)_4}{(W/L)_3} = I_D$$

6.26

Refer to Fig. P6.26:

$$V_{DS2} \leq V_{GS2} - V_{EP} \Rightarrow V_{DSmax} = V_{GS2} - V_E$$

$$(1.3 - 1.5) = V_{GS2} - (-0.6) \Rightarrow V_{GS2} = -0.8 \text{ V} = V_{GS1}$$

For Q_1 :

$$I_{D1} = 20 \mu\text{A} = \frac{1}{2} \times 80 \times \frac{W_1}{L} \times (-0.8 + 0.6)^2$$

$$\Rightarrow W_1 = 10 \mu\text{m}$$

$$I_2 = 100 \mu\text{A} = 5 I_{REF} \Rightarrow W_2 = 5 W_1 = 50 \mu\text{m}$$

$$I_3 = I_{REF} \Rightarrow W_3 = W_1 = 10 \mu\text{m}$$

$$I_3 = I_4 \Rightarrow \frac{W_3}{W_4} = \frac{M_n}{M_p} \Rightarrow W_4 = 10 \times \frac{80}{200} = 4 \mu\text{m}$$

For Q_5 : $V_{DS5} = V_{GS5} - V_{tn}$ for lowest V_D

$$(-1.3 - (-1.5)) = V_{GS5} - 0.6 \Rightarrow V_{GS5} = 0.8 \text{ V}$$

$$I_5 = 50 \mu\text{A} = \frac{1}{2} \times 200 \times \frac{W_5}{L} \times (0.8 - 0.6)^2 \Rightarrow W_5 = 10 \mu\text{m}$$

Now we calculate R :

$$V_{GS2} = -0.8 \text{ V} \Rightarrow V_{G2} = 1.5 - 0.8 = 0.7 \text{ V}$$

$$R = V_{G2} / I_{REF}$$

$$R = \frac{0.7}{20 \mu\text{A}} = 35 \text{ k}\Omega$$

$$R = 35 \text{ k}\Omega$$

$$r_{D2} = \frac{V_A L}{I_D} = \frac{12 \times 0.8}{0.1} = 96 \text{ k}\Omega, r_{D5} = \frac{10 \times 0.8}{0.05} = 160 \text{ k}\Omega$$

6.27

If the transistor with $W=10$ is diode-connected,

then: $I_2 = 100 \times \frac{20}{10} = 200 \mu\text{A}$

$I_3 = 100 \times \frac{40}{10} = 400 \mu\text{A}$

If the transistor with $W=20$ is diode-connected

then: $I_2 = 100 \times \frac{10}{20} = 50 \mu\text{A}$

$I_3 = 100 \times \frac{40}{20} = 200 \mu\text{A}$

If the transistor with $W=40$ is diode-connected,

then: $I_2 = 100 \times \frac{10}{40} = 25 \mu\text{A}$

$I_3 = 100 \times \frac{20}{40} = 50 \mu\text{A}$

So far cases that only one transistor is diode connected, 4 different output currents are possible (depending on the configuration we choose).

If 2 transistors are diode-connected, then they act as an equivalent transistor whose width is the sum of the widths of each transistor:

If $W_{\text{eff}} = 10 + 20$ then $I_0 = 100 \times \frac{40}{30} = 133 \mu\text{A}$

If $W_{\text{eff}} = 20 + 40$ then $I_0 = 100 \times \frac{10}{60} = 16.7 \mu\text{A}$

If $W_{\text{eff}} = 40 + 10$ then $I_0 = 100 \times \frac{20}{50} = 40 \mu\text{A}$

So 3 different output currents are possible depending on which two transistors are diode-connected. Now we calculate V_{SG} :

$100 = \frac{1}{2} \times 80 \times \frac{30}{1} (V_{SG} - 0.7)^2 \Rightarrow V_{SG} = 1 \text{ V for } W_{\text{eff}} = 30 \mu\text{m}$
all have the same V_{SG} for any given configuration.

For $W_{\text{eff}} = 60 \Rightarrow 100 = \frac{1}{2} \times 80 \times \frac{60}{1} (V_{SG} - 0.7)^2$
 $\Rightarrow V_{SG} = 0.9 \text{ V}$

For $W_{\text{eff}} = 50 \Rightarrow 100 = \frac{1}{2} \times 80 \times \frac{50}{1} (V_{SG} - 0.7)^2$
 $\Rightarrow V_{SG} = 0.93 \text{ V}$

6.28

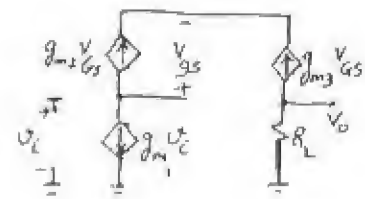
$-g_{m2} V_{GS} = g_{m1} V_i$

$\Rightarrow V_{GS} = -\frac{g_{m1}}{g_{m2}} V_i$

$V_0 = -R_L g_{m3} V_{GS}$

$V_0 = -R_L g_{m3} \left(-\frac{g_{m1}}{g_{m2}} V_i\right)$

$\frac{V_0}{V_i} = +R_L g_{m1} \frac{g_{m3}}{g_{m2}} = R_L g_{m1} \frac{W_3}{W_2}$



Note that since Q_2, Q_3 have the same V_{GS} and therefore the same V_{OV} : $\frac{g_{m3}}{g_{m2}} = \frac{I_3}{I_2} = \frac{W_3}{W_2}$

6.29

$I_3 = 10^{-15} \text{ A}$

a) $I_{\text{REF}} = I_3 \leq \frac{V_{BE}}{V_T} \Rightarrow V_{BE} = V_T \ln \frac{I_{\text{REF}}}{I_3}$

$I_{\text{REF}} = 10 \mu\text{A} \Rightarrow V_{BE} = 0.025 \ln \frac{10 \times 10^{-6}}{10^{-15}} = 0.576 \text{ V}$

$I_{\text{REF}} = 10 \text{ mA} \Rightarrow V_{BE} = 0.025 \ln \frac{10 \times 10^{-3}}{10^{-15}} = 0.748 \text{ V}$

Therefore:

$10 \mu\text{A} \leq I_{\text{REF}} \leq 10 \text{ mA} \Rightarrow 0.576 \text{ V} \leq V_{BE} \leq 0.748 \text{ V}$

Since β is very high, I_B is negligible and hence

$I_0 \approx I_{\text{REF}} : 10 \mu\text{A} \leq I_0 \leq 10 \text{ mA}$

b) $I_0 = I_{\text{REF}} \frac{1}{1 + 2/\beta}$ (Eq. 6.21)

For $0.1 \text{ mA} \leq I_0 \leq 5 \text{ mA}$, β remains constant at 100.

$I_{\text{REF}} = 10 \text{ mA} \Rightarrow I_0 = \frac{10}{1 + \frac{2}{100}} = 9.72 \text{ mA}$

$I_{\text{REF}} = 0.1 \text{ mA} \Rightarrow I_0 = \frac{0.1}{1 + \frac{2}{100}} = 0.098 \text{ mA}$

$I_{\text{REF}} = 1 \text{ mA} \Rightarrow I_0 = \frac{1}{1 + \frac{2}{100}} = 0.98 \text{ mA}$

$I_{\text{REF}} = 10 \mu\text{A} \Rightarrow$

6.30

$$I_{S2} = I_{S1} \cdot m, \quad I_{C1} = I_C$$

$$I_{REF} = I_C + \frac{I_C}{\beta} + \frac{I_0}{\beta} \quad (1)$$

$$V_{BE1} = V_{BE2} \Rightarrow$$

$$V_T \ln \frac{I_C}{I_{S1}} = V_T \ln \frac{I_0}{I_{S2}}$$

$$\Rightarrow \frac{I_0}{I_C} = \frac{I_{S2}}{I_{S1}} = m \Rightarrow I_C = I_0/m$$

by substituting for I_C in (1):

$$I_{REF} = \frac{I_0}{m} + \frac{I_0}{m\beta} + \frac{I_0}{\beta} \Rightarrow \frac{I_0}{I_{REF}} = \frac{m}{1 + \frac{1}{\beta} + \frac{m}{\beta}}$$

$$\frac{I_0}{I_{REF}} = \frac{m}{1 + \frac{1+m}{\beta}}$$

This result is the same as Eq. 6.22.

For large β , $I_0/I_{REF} = m$, with finite β this ratio drops to $I_0/I_{REF} = \frac{m}{1 + \frac{1+m}{\beta}}$. To keep the introduced error within 5%: $0.95m = \frac{m}{1 + \frac{1+m}{\beta}}$

$$\beta_{min} = 80 \Rightarrow 0.95 = \frac{1}{1 + \frac{1+m}{80}} \Rightarrow m = 3.21$$

6.31

The transfer ratio is the same as Eq. 6.21:

$$\frac{I_0}{I_{REF}} = \frac{1}{1 + \frac{2}{\beta}}$$

$$\beta = 20 \Rightarrow \frac{I_0}{I_{REF}} = \frac{1}{1 + \frac{2}{20}} = 0.91$$

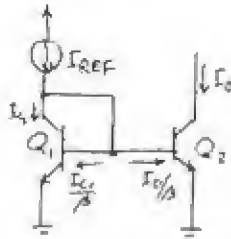
6.32

$$I_0 = I_{REF} = 2 \text{ mA}$$

$$r_{02} = \frac{V_{A2}}{I_0} = \frac{90}{2} = 45 \text{ k}\Omega$$

$$r_{02} = \frac{\Delta V_0}{\Delta I_0} \Rightarrow \frac{10-1}{\Delta I_0} = 45 \Rightarrow \Delta I_0 = 0.2 \text{ mA}$$

$$\frac{\Delta I_0}{I_0} = \frac{0.2}{2} = 10\% \text{ change}$$



6.33

$$I_S = 10^{-15} \text{ A}, \quad \beta = 50$$

$$\frac{I_0}{I_{REF}} = \frac{1}{1 + \frac{2}{\beta}} \Rightarrow I_{REF} = I_0 \left(1 + \frac{2}{\beta}\right) = 1 \text{ mA} \left(1 + \frac{2}{50}\right)$$

$$I_{REF} = 1.02 \text{ mA}$$

$$V_{BE} = V_T \ln \frac{I_0}{I_S (1 + V_{CE}/V_A)} = 0.025 \ln \frac{10^{-3}}{10^{-15} (1 + \frac{2}{50})} = 0.689 \text{ V}$$

$$V_C = V_D = 5 - 0.689 = 4.31 \text{ V}$$

$$V_C = R_A I_{REF} \Rightarrow R = \frac{4.31}{1.02} = 4.2 \text{ k}\Omega$$

$$r_0 = \frac{V_A}{I_0} = \frac{50}{1} = 50 \text{ k}\Omega$$

V_{omax} occurs when Q_2 is on the edge of saturation or $V_{CE} = 0.3 \text{ V}$. Therefore V_{omax} is $5 - 0.3 = 4.7 \text{ V}$

$$r_0 = \frac{\Delta V_0}{\Delta I_0} \Rightarrow \frac{4.7 - (-5)}{\Delta I_0} = 50 \text{ k}\Omega \Rightarrow \Delta I_0 = 0.194 \text{ mA}$$

$$\frac{\Delta I_0}{I_0} \times 100 = \frac{0.194}{1} \times 100 = 19.4\% \text{ change in } I_0$$

6.34

$$I_{C1} = I_{C2} = I_{R1}$$

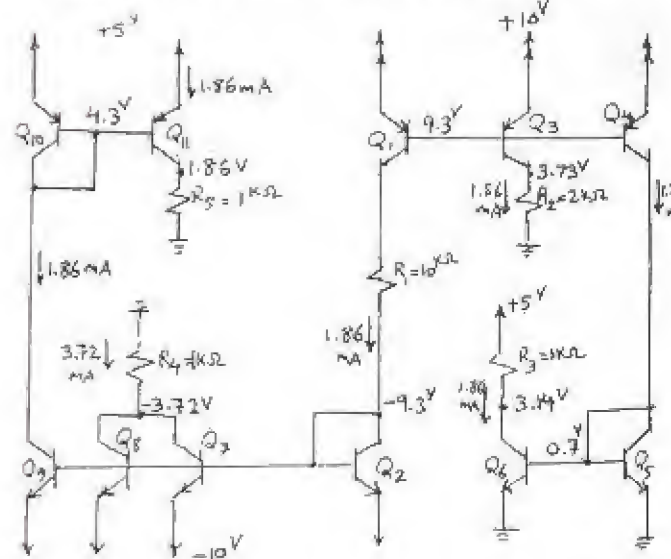
$$V_{D1} = 10 - 0.7 = 9.3 \text{ V}, \quad V_{D2} = -10 + 0.7 = -9.3 \text{ V}, \quad I_{R1} = \frac{9.3 + 9.3}{R_1}$$

$$\Rightarrow I_{R1} = 1.86 \text{ mA} = I_{C1} = I_{C2} = I_{C3} = I_{C4} = I_{C5} = I_{C6}$$

$$V_{C3} = 1.86 \times 2 \text{ k}\Omega = 3.72 \text{ V}, \quad V_{C5} = 0.7 \text{ V}$$

$$V_{C6} = 5 - 1.86 \times 1 \text{ k}\Omega = 3.14 \text{ V}, \quad I_{C9} = I_{C8} = I_{C7} = I_{C2} = 1.86 \text{ mA}$$

$$I_{R4} = 2 \times 1.86 = 3.72 \text{ mA} \Rightarrow V_{C2} = -3.72 \times 1 \text{ k}\Omega = -3.72 \text{ V}$$



Cont.

$$I_{C10} = I_{C9} = 1.86 \text{ mA}$$

$$V_{C9} = V_{C10} = V_{B10} = 5 - 0.7 = 4.3 \text{ V}$$

$$I_{C11} = I_{C10} = 1.86 \text{ mA}$$

$$V_{C11} = 1.86 \times 1 = 1.86 \text{ V}$$

6.35

a) Refer to Fig. P6.35

$$R = 10 \text{ k}\Omega$$

$$V_1 = -0.7 \text{ V} \Rightarrow I_{C1} = \frac{-0.7 - (-10.7)}{10 \text{ k}} = 1 \text{ mA}$$

$$I_{C1} = 1 \text{ mA}$$

$$V_2 = 5.7 - 0.7 = 5 \text{ V}$$

$$I = I_{C3} + I_{C4} \quad , \quad I_{C3} = I_{C4} = I_{C1} \Rightarrow I = 2 \times 1 = 2 \text{ mA}$$

$$V_3 = 0 + 0.7 = 0.7 \text{ V}$$

$$V_4 = -10.7 + 1 \times 10 \text{ k} = -0.7 \text{ V}$$

$$V_5 = -10.7 + 1 \times \frac{10 \text{ k}}{2} = -5.7 \text{ V}$$

b) $R = 100 \text{ k}\Omega$

$$V_1 = -0.7 \text{ V} \Rightarrow I_{C1} = \frac{-0.7 + 10.7}{100 \text{ k}} = 0.1 \text{ mA}$$

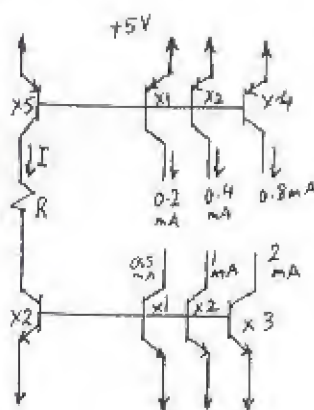
$$I = 2 I_{C1} = 0.2 \text{ mA}$$

$$V_3 = 0.7 \text{ V} \quad , \quad V_2 = 5.7 - 0.7 = 5 \text{ V}$$

$$V_4 = -10.7 + \frac{1 \times 100}{2} = -0.7 \text{ V}$$

$$V_5 = -10.7 + 0.1 \times \frac{100}{2} = -5.7 \text{ V}$$

6.36



$$I = \frac{10 - 1.4}{R} = 1 \text{ mA}$$

$$\Rightarrow R = 8.6 \text{ k}\Omega$$

6.37

a) Refer to Fig. P6.37.

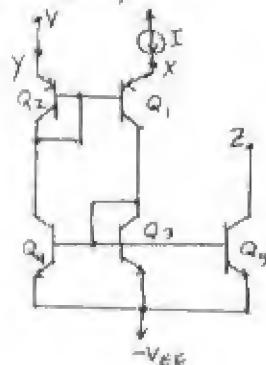
Since Q_1, Q_3 have equal currents, I_1 and Q_3 and Q_4 have equal V_{BE} which results in equal currents, then Q_2 has the same current as Q_1 .

$$\text{Therefore: } V_{BE1} = V_{BE2} \Rightarrow V_X = V_Y = V$$

$$\text{Also, } V_{BE5} = V_{BE3}$$

$$\Rightarrow I_5 = I_3 = I$$

$$\text{or } I_2 = I.$$



$$b) I_2 = I_4 \quad , \quad I_1 = I_3$$

Since $V_{BE4} = V_{BE3}$ then

$$I_3 = I_4 \text{ and hence } I_1 = I_2.$$

From $I_1 = I_2$ we conclude

$$\text{that } V_{BE1} = V_{BE2} \text{ and}$$

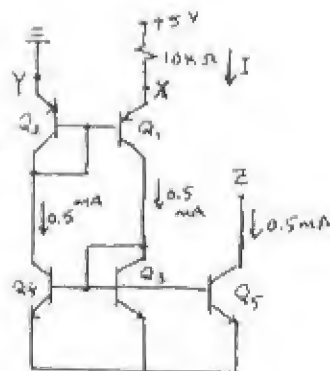
Since $V_{B1} = V_{B2}$ then V_{E1}

has to be the same as

$$V_{E2}: V_{E1} = V_{E2} = 0$$

$$V_X = 0$$

$$I = \frac{5 - 0}{10 \text{ k}} = 0.5 \text{ mA}$$



6.38

$$40 \text{ dB} = 20 \log A_o \Rightarrow A_o = 100 \text{ V/V}$$

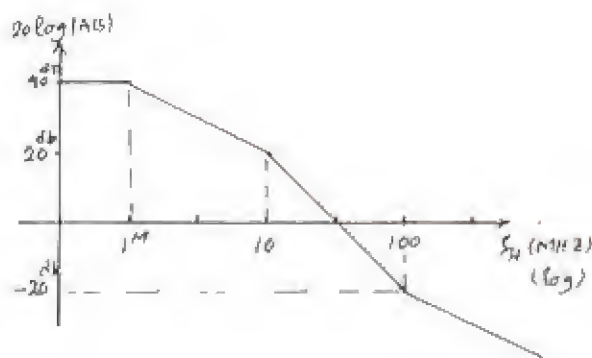
$$A(s) = +100 \frac{(1 + \frac{5/100 \times 10^6 \times 2\pi}{s})}{(1 + \frac{5}{2\pi \times 10^3 s})(1 + \frac{5}{2\pi \times 10^6 s})}$$

$$A(s) = +100 \frac{(1 + \frac{5}{2\pi \times 10^3 s})}{(1 + \frac{5}{2\pi \times 10^3 s})(1 + \frac{5}{2\pi \times 10^6 s})}$$

$$\text{Eq. 6-36} = 10 \text{ Hz} = \frac{1}{\sqrt{(\frac{1}{2\pi \times 10^3})^2 + (\frac{1}{2\pi \times 10^6})^2 - 2(\frac{1}{2\pi \times 10^3})^2}}$$

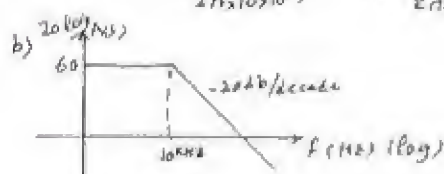
$$f_H = 0.995 \text{ MHz}$$

Cont.



6.39

$$a) A(s) = \frac{1000}{(1 + \frac{s}{2\pi \times 10^5})} = \frac{1000}{(1 + \frac{s}{2\pi \times 10^6})}$$



6.40

$$F_H(s) = \frac{1}{(1 + \frac{s}{\omega_{p1}})(1 + \frac{s}{\omega_{p2}})} \quad \omega_H < \omega_{p2}$$

using dominant pole approximator: $\omega_H \approx \omega_{p1}$

using the root sum of squares formula:

$$\omega_H = \frac{1}{\sqrt{\frac{1}{\omega_{p1}^2} + \frac{1}{\omega_{p2}^2}}} = \frac{\omega_{p1}}{\sqrt{1 + (\frac{\omega_{p1}}{\omega_{p2}})^2}}$$

The difference between the two estimates for ω_H is:

$$\Delta \omega_H = \omega_{p1} - \frac{\omega_{p1}}{\sqrt{1 + (\frac{\omega_{p1}}{\omega_{p2}})^2}}$$

$$\text{If } n = \frac{\omega_{p2}}{\omega_{p1}}: \quad \frac{\Delta \omega_H}{\omega_{p1}} = 1 - \frac{1}{\sqrt{1 + \frac{1}{n^2}}}$$

$$\text{for } \frac{\Delta \omega_H}{\omega_{p1}} = 10\% = 0.1 \Rightarrow n = 2.07$$

$$\text{for } \frac{\Delta \omega_H}{\omega_{p1}} = 1\% = 0.01 \Rightarrow n = 7.02$$

6.41

$$A(s) = -100 \frac{1 + \frac{s}{10^6}}{(1 + \frac{s}{10^5})(1 + \frac{s}{10^7})}$$

$$a) \omega_H \approx 10^5 \text{ rad/s}$$

$$b) \omega_H = \frac{1}{\sqrt{(\frac{1}{10^5})^2 + (\frac{1}{10^7})^2 - 2(\frac{1}{10^6})^2}} = 101 \text{ Krad/s}$$

If the pole at 10^6 rad/s is lowered to 10^5 rad/s , the transfer function becomes:

$$A(s) = \frac{-100}{1 + \frac{s}{10^5}} \Rightarrow f_H = \frac{10^5}{2\pi} \text{ Hz}$$

6.42

$$30^\circ = 3 \tan^{-1} \frac{\omega}{\omega_p} = 3 \tan^{-1} \frac{10^6}{\omega_p} \Rightarrow \omega_p = 5.67 \times 10^6 \text{ rad/s}$$

6.43

$$\omega_H = \frac{1}{C_{gs}R' + C_{gd}} = \frac{1}{C_{gs}R_{gs} + C_{gd}R_{gd}}$$

$$\omega_H = \frac{1}{C_{gs}R' + C_{gd}(R' + R'_L + g_m R'_L R')} \quad (\text{From Example 6.1})$$

For $C_{gs} = C_{gd} = 1 \text{ pF}$, $R'_L = 3.33 \text{ k}\Omega$, $g_m = 4 \text{ mA/V}$

$$\omega_H = \frac{1}{10^{-12}R' + 10^{-12}(R' + 3.33 \times 10^3 + 4 \times 3.33 \times R')}$$

To obtain $\omega_H = 2\pi \times 150 \times 10^3$

$$2\pi \times 150 \times 10^3 = \frac{10^{12}}{3.33 \times 10^3 + 15.32R'} \Rightarrow R' = 69.04 \text{ k}\Omega$$

$$R' = R \parallel R_{in} = R \parallel 420 \text{ k}\Omega = 69.04 \Rightarrow R = 82.6 \text{ k}\Omega$$

6.44

$$\text{Pole at } \frac{1}{2\pi \times 10^4 \times 5 \times 10^{-12}} = 3.18 \text{ MHz} \quad \text{and} \quad \text{Cont}$$

pole at $\frac{1}{2\pi \times 20 \times 10^3 \times 2 \times 10^{-12}} = 3.98 \text{ MHz}$

Since both poles are relatively close together, we use the root-sum-of-squares formula.

$$f_H = \frac{1}{\sqrt{\frac{1}{3.18^2} + \frac{1}{3.98^2}}} = 2.5 \text{ MHz}$$

Manufactured design:

Poles at $\frac{1}{2\pi \times 10^4 \times 15 \times 10^{-12}} = 1.06 \text{ MHz}$ and at

$$\frac{1}{2\pi \times 20 \times 10^3 \times 12 \times 10^{-12}} = 0.66 \text{ MHz}$$

$$f_H = \frac{1}{\sqrt{\frac{1}{1.06^2} + \frac{1}{0.66^2}}} = 0.56 \text{ MHz}$$

6.45

Refer to solution of Example 6.6:

$$A_M = \frac{V_o}{V_i} = -\frac{R_{in}}{R_{in} + R} g_m R'_L = -\frac{1.2}{1.2 + 0.1} (2 \times 12)$$

$$A_M = -22.2 \text{ V/V}$$

$$R_{gs} = R_{in} \parallel R = 1.2 \parallel 0.1 = 92.3 \text{ k}\Omega$$

$$\tau_{gs} = R_{gs} C_{gs} = 1 \times 10^{-12} \times 92.3 \times 10^3 = 92.3 \text{ ns}$$

$$R_{gd} = R'_L + R'_L + g_m R'_L R' \text{ where } R' = R_{in} \parallel R = 92.3 \text{ k}\Omega$$

$$R_{gd} = 42.3 + 12 + 2 \times 12 \times 92.3 = 2.32 \text{ M}\Omega$$

$$\tau_{gd} = C_{gd} R_{gd} = 1 \times 10^{-12} \times 2.32 \times 10^6 = 2320 \text{ ns}$$

$$\omega_H = \frac{1}{\tau_{gs} + \tau_{gd}} = \frac{1}{(92.3 + 2320) \times 10^{-9}} = 414.5 \text{ krad/s}$$

$$f_H = 66 \text{ kHz}$$

6.46

a) $V_o = -g_m R_{gs} V_{gs}$ ①
 $V_{gs} = V_{sig} - R_{gs} g_m V_{gs}$
 $V_{gs}(1 + g_m R_{gs}) = V_{sig}$

① $\Rightarrow V_o = \frac{-g_m R_{gs}}{1 + g_m R_{gs}} V_{sig} \Rightarrow \frac{V_o}{V_{sig}} = \frac{-g_m R_{gs}}{1 + g_m R_{gs}}$

b) $V_S = (g_m V_X - i_X) R_S$
 $V_G = V_S + V_X = (g_m V_X - i_X) R_S + V_X$
 $\Rightarrow i_X = \frac{V_G}{R} = \frac{(1 + g_m R_S) V_X - i_X R_S}{R}$
 $R_{gs} = \frac{V_X}{i_X} = \frac{1 + R_S/R}{1 + g_m R_S} = \frac{R + R_S}{1 + g_m R_S}$ (R is R_{sig})

to calculate R_{gd} :

$V_G = -R i_X$
 $V_S = -R i_X - V_{gs}$
 $V_S = R_S i_X = g_m V_{gs}$
 $R_S g_m V_{gs} = -R i_X - V_{gs} \Rightarrow V_{gs} = \frac{-R i_X}{1 + g_m R_S}$

At D: $i_X = g_m V_{gs} + \frac{V_X - R_L i_X}{R_L}$

substitute V_{gs} : $i_X = -\frac{g_m R i_X}{1 + g_m R_S} + \frac{V_X}{R_L} - \frac{R_L i_X}{R_L}$

$$i_X \left[1 + \frac{g_m R}{1 + g_m R_S} + \frac{R}{R_L} \right] = \frac{V_X}{R_L}$$

$$R_{gd} = \frac{V_X}{i_X} = R_L + R + \frac{g_m R R_L}{1 + g_m R_S} \quad (R \text{ is } R_{sig})$$

c) $R_S = 0$:

$$\frac{V_o}{V_{sig}} = \frac{-4 \times 5}{1 + 4 \times 0} = -20 \text{ V/V}$$

$$R_{gs} = R_{sig} = 100 \text{ k}\Omega$$

$$R_{gd} = 5 \text{ k}\Omega + 100 \text{ k}\Omega + 4 \times 5 \times 100 = 2105 \text{ k}\Omega$$

$$\omega_H \approx \frac{1}{C_{gs} R_{gs} + C_{gd} R_{gd}} = \frac{1}{10^{-12} \times 100 \times 10^3 + 10^{-12} \times 2105 \times 10^3}$$

$$\omega_H \approx 453.5 \text{ krad/s}$$

$$|Gain| \times \text{Bandwidth} = 20 \times 453.5 = 9.07 \text{ Mrad/s}$$

$R_S = 100 \Omega$:

$$\frac{V_o}{V_{sig}} = \frac{-4 \times 5}{1 + 4 \times 0.1} = -14.3 \text{ V/V}$$

$$R_{gs} = \frac{100 + 0.1}{1 + 4 \times 0.1} = 71.5 \text{ k}\Omega$$

$$R_{gd} = 5 + 100 + \frac{4 \times 5 \times 100}{1 + 4 \times 0.1} = 1533.6 \text{ k}\Omega$$

$$\omega_H = \frac{1}{10^{-12} \times 71.5 \times 10^3 + 10^{-12} \times 1533.6 \times 10^3} = 623 \text{ krad/s}$$

Cont.

$$|Gain| \times \text{Bandwidth} = 14.3 \times 623^k = 8.91 \text{ Mrad/s}$$

$$R_S = 250 \Omega$$

$$\frac{V_o}{V_{sig}} = \frac{-4 \times 5}{1 + 4 \times 0.25} = -10 \text{ V/V}$$

$$R_{gs} = \frac{100 + 0.25}{1 + 4 \times 0.25} = 50.1 \text{ k}\Omega$$

$$R_{gd} = 5 + 100 + \frac{4 \times 5 \times 100}{1 + 4 \times 0.25} = 110.5 \text{ k}\Omega$$

$$\omega_H = \frac{1}{10^{-12} \times 50.1 \times 10^3 + 10^{-12} \times 110.5 \times 10^3} = 865.7 \text{ krad/s}$$

$$|gain| \times \text{Bandwidth} = 10 \times 865.7^k = 8.66 \text{ Mrad/s}$$

Summary table:

$R_S^{(A)}$	Gain (V/V)	ω (krad/s)	Gain-BW product (Mrad/s)
0	-20	453.5	9.07
100	-14.3	623.0	8.91
250	-10	865.7	8.66

The Gain-Bandwidth is approximately constant.

6.48

If we assume that capacitors are perfect open circuits for midband, then:

$$A_M = \frac{V_o}{V_{sig}} = \frac{-R_{in}}{R_{in} + R_{sig}} (g_m R'_L) = \frac{-650}{650 + 150} (5 \times 10) = -40.6 \text{ V/V}$$

$$\tau_{gs} = C_{gs} R_{gs} = C_{gs} (R_{in} \parallel R_{sig}) = 2^p \times (150^k \parallel 1650^k)$$

$$\tau_{gs} = 243.75 \text{ ns}$$

$$\tau_{gd} = C_{gd} R_{gd} \quad , \text{ Refer to Example 6.6}$$

$$R_{gd} = R'_L + R'_L + g_m R'_L R'_L \Rightarrow R_{gd} = 121.9 + 10 + 5 \times 10 \times 121.9$$

$$R'_L = 150^k \parallel 1650^k = 121.9 \text{ k}\Omega$$

$$R_{gd} = 6.2 \text{ M}\Omega$$

$$\tau_{gd} = C_{gd} R_{gd} = 0.5^p \times 6.2^M = 3100 \text{ ns}$$

$$\tau_L = R'_L C_L = 10^k \times 3^p = 30 \text{ ns}$$

$$\omega_H = \frac{1}{\tau_{gs} + \tau_{gd} + \tau_L} = \frac{1}{307 + 3100 + 243.75 \text{ ns}} = 296.4 \text{ krad/s}$$

$$f_H = 47.2 \text{ kHz}$$

6.47

$$A_M = \frac{V_o}{V_{sig}} = - \frac{R_{in}}{R_{in} + R_{sig}} (g_m R'_L) = - \frac{5}{5 + 1} (0.3 \times 100^k)$$

$$A_M = -25 \text{ V/V} \quad \text{Now refer to Example 6.6.}$$

$$R_{gs} = R_{in} \parallel R_{sig} = 5 \text{ M}\Omega \parallel 1 \text{ M}\Omega = 0.83 \text{ M}\Omega$$

$$\tau_{gs} = R_{gs} C_{gs} = 0.2 \times 10^{-12} \times 0.83 \times 10^6 = 166.7 \text{ ns}$$

$$R_{gd} = R'_L + R'_L + g_m R'_L R'_L$$

$$R'_L = R_{in} \parallel R_{sig} = 0.83 \text{ M}\Omega \quad \Rightarrow R_{gd} = 0.83 + 0.1 + 0.83 \times 0.3 \times 100$$

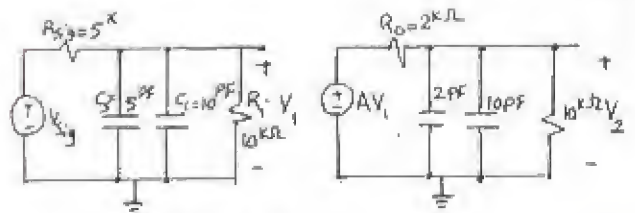
$$R_{gd} = 25.92 \text{ M}\Omega$$

$$\tau_{gd} = C_{gd} R_{gd} = 25.92 \times 10^{-6} \times 0.1 \times 10^{-12} = 2592 \text{ ns}$$

$$\omega_H \approx \frac{1}{\tau_{gs} + \tau_{gd}} = \frac{1}{(166.7 + 2592) \times 10^{-9}} = 362.5 \text{ krad/s}$$

$$f_H = 57.7 \text{ kHz}$$

6.49



$$\tau_1 = (5^p + 10^p) \times (5^k \parallel 10^k)$$

$$\tau_1 = 50 \text{ ns}$$

$$\omega_1 = \frac{1}{\tau_1} = 20 \text{ Mrad/s}$$

$$\tau_2 = (2^p + 10^p) (10^k \parallel 2^k)$$

$$\tau_2 = 20 \text{ ns}$$

$$\omega_2 = \frac{1}{\tau_2} = 50 \text{ Mrad/s}$$

$$\tau_3 = (2^p + 7^p) (1^k \parallel 2^k)$$

$$\tau_3 = 6 \text{ ns}$$

$$\omega_3 = 166 \text{ Mrad/s}$$

$$\omega_H \approx \frac{1}{\tau_1 + \tau_2 + \tau_3} = \frac{1}{50 + 20 + 6 \text{ ns}} = 13.2 \text{ MHz}$$

$$f_H = 2.1 \text{ MHz}$$

6.50

$$\text{Eq. 6.41 } \omega_H \approx \frac{1}{\sum R C}$$

$$a) \omega_H = \frac{1}{20 + 5 + 1} = 38.46 \text{ Mrad/s} \Rightarrow f_H = 6.12 \text{ MHz}$$

$$b) \omega_H = \frac{1}{\frac{1}{\omega_{p1}} + \frac{1}{\omega_{p2}} + \frac{1}{\omega_{p3}}} \quad (\text{Eq. 6.38})$$

$$\omega_H = \frac{2\pi}{\frac{1}{f_1} + \frac{1}{f_2} + \frac{1}{f_3}} = \frac{2\pi}{\frac{1}{50} + \frac{1}{200} + \frac{1}{1000}} = 241.5 \text{ Mrad/s}$$

$$f_H = 38.46 \text{ MHz}$$

$$c) \omega_H = \frac{1}{\frac{1}{50} + \frac{1}{200} + \frac{1}{1000}} = 38.46 \text{ Mrad/s}$$

$$f_H = 6.12 \text{ MHz}$$

$$d) \omega_H = \frac{1}{1000 + 200 + 200} = 714 \text{ Krad/s} \Rightarrow f_H = 113.7 \text{ KHz}$$

$$e) \omega_H = \frac{1}{0.4 + 1} = 714 \text{ Krad/s} \Rightarrow f_H = 113.7 \text{ KHz}$$

$$f) \omega_H = \frac{1}{1 + 0.2 + 0.5} = 741 \text{ Krad/s} \Rightarrow f_H = 118 \text{ KHz}$$

$$g) \omega_H = \frac{2\pi}{\frac{1}{f_1} + \frac{1}{f_2} + \frac{1}{f_3} + \frac{1}{f_4}} = \frac{2\pi}{\frac{1}{1} + \frac{1}{2} + \frac{1}{5} + \frac{1}{5}}$$

$$\omega_H = 3.36 \text{ Mrad/s} \Rightarrow f_H = 526 \text{ MHz}$$

6.51

$$R_{in} = \frac{R}{1 - \text{Gain}} = \frac{100}{1 - 0.95} = 2000 \text{ k}\Omega = 2 \text{ M}\Omega$$

6.52

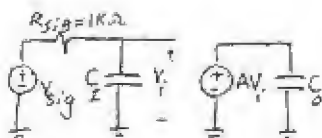
$$\text{Eq. 6.44a } Z_1 = Z_{1+k} \Rightarrow C_1 = 0.1 \times (1 - (-1000))$$

$$\Rightarrow C_1 = 100.1 \text{ pF}$$

$$C_0 = 0.1 \times \left(\frac{-1}{1000} + 1 \right)$$

$$C_0 = 99.9 \text{ pF}$$

(using Miller's Theorem)



$$V_o = A V_i = A \times V_{sig} \times \frac{1/C_1 s}{R_{sig} + 1/C_1 s} \Rightarrow \frac{V_o}{V_{sig}} = \frac{A}{1 + C_1 R_{sig} s}$$

$$\omega_H = \frac{1}{C_1 R_{sig}} = \frac{1}{100.1 \times 10^{-12} \times 10^3} = 9.99 \text{ Mrad/s} \Rightarrow f_H = 1.59 \text{ MHz}$$

To calculate unity gain frequency:

$$| \text{Gain} | = 1$$

$$\frac{V_o}{V_i} = \frac{A}{1 + C_1 R_{sig} s} = \frac{-1000}{1 + 100.1 \times 10^{-12} s} \quad (s = j\omega)$$

$$\frac{1000}{\sqrt{1 + (100.1 \times 10^{-12} \times \omega)^2}} = 1 \Rightarrow \omega \approx 10 \text{ Grad/s}$$

$$f_T \approx 1.59 \text{ GHz}$$

As we can see $f_T \approx f_H \times A$

6.53

Using Miller's Theorem, in each case the capacitance at the input is $C(1-A)$ and the capacitance at the output is $C(1-\frac{1}{A})$. Thus:

$$a) A = -1000 \text{ V/V and } C = 1 \text{ pF}$$

$$C_i = 1.001 \text{ nF and } C_o = 1.001 \text{ pF}$$

$$b) A = -10 \text{ V/V and } C = 10 \text{ pF}$$

$$C_i = 11 \text{ pF and } C_o = 11 \text{ pF}$$

$$c) A = -1 \text{ V/V and } C = 10 \text{ pF}$$

$$C_i = 20 \text{ pF and } C_o = 20 \text{ pF}$$

$$d) A = 1 \text{ V/V and } C = 10 \text{ pF}$$

$$C_i = 0 \text{ pF and } C_o = 0 \text{ pF}$$

$$e) A = 10 \text{ V/V and } C = 10 \text{ pF}$$

$$C_i = -90 \text{ pF and } C_o = 9 \text{ pF}$$

In (e) the negative capacitance at the input can be used to cancel the effect of the input capacitance of the amplifier.

6.54

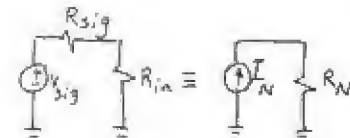
$$a) R_{in} = \frac{R}{1-A} = \frac{R}{1-2} = -R \quad (\text{Miller's theorem})$$

$$b) I_N = \frac{V_{sig}}{R_{sig}}$$

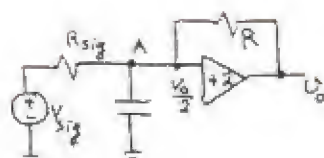
$$R_N = R_{sig} \parallel R_{in}$$

If $R_{sig} = R$ then:

$$R_N = R \parallel (-R) = \infty \Rightarrow I_L = I_N = \frac{V_{sig}}{R_{sig}} = \frac{V_{sig}}{R} \quad \text{Cont.}$$



KCL at A:



$$\frac{V_o - V_{sig}}{R_{sig}} + \frac{V_o}{2} \times C S + \frac{-V_o}{2R} = 0$$

$$\text{If } R_{sig} = R \Rightarrow \frac{V_{sig}}{R} = \frac{V_o}{2} C S \Rightarrow \frac{V_o}{V_{sig}} = \frac{2}{R C S}$$

6.55

From Table 6.3 we have:

$$\text{Intrinsic gain} = g_m r_o = \frac{2V_A L}{V_{ov}}$$

$$\Rightarrow \text{Intrinsic gain} = \frac{2 \times 10 \times V_{ov}}{0.2} = 100 V/V$$

$$g_m r_o = 100 V/V$$

$$g_m = \frac{2I_D}{V_{ov}} \Rightarrow I_D = \frac{g_m V_{ov}}{2} = \frac{2 \times 0.2}{2} = 0.2 \text{ mA}$$

$$g_m = \mu_n C_{ox} \frac{W}{L} V_{ov} \Rightarrow W = \frac{g_m L}{\mu_n V_{ov}} = \frac{2 \times 10^{-3}}{125 \times 0.2} = 80 \mu\text{m}$$

6.56

$$A_0 = g_m r_o = 100 V/V = \frac{2V_A L}{V_{ov}}$$

$$I_D = \frac{1}{2} K_n \frac{W}{L} V_{ov}^2 = 100 \mu\text{A}$$

$$\frac{A_{02}}{A_{01}} = \frac{V_{ov1}}{V_{ov2}} = \sqrt{\frac{I_{D1}}{I_{D2}}} \Rightarrow A_{02} = A_{01} \sqrt{\frac{I_{D1}}{I_{D2}}}$$

$$\text{Now if } I_D \text{ is } 25 \mu\text{A then: } A_{02} = 100 \sqrt{\frac{100}{25}} = 200 V/V$$

$$I_D = 400 \mu\text{A} \Rightarrow A_{02} = 100 \sqrt{\frac{100}{400}} = 50 V/V$$

$$g_m = \sqrt{2 \mu_n C_{ox} \frac{W}{L} I_D} \Rightarrow \frac{g_{m2}}{g_{m1}} = \sqrt{\frac{I_{D2}}{I_{D1}}} \Rightarrow g_{m2} = g_{m1} \sqrt{\frac{I_{D2}}{I_{D1}}}$$

$$\text{For } I_D = 25 \mu\text{A} \quad g_{m2} = g_{m1} \sqrt{\frac{25}{100}} \Rightarrow g_{m2} = g_{m1}/2$$

$$I_D = 400 \mu\text{A} \Rightarrow g_{m2} = g_{m1} \sqrt{\frac{400}{100}} \Rightarrow g_{m2} = 2g_{m1}$$

6.57

Refer to Fig. PB.57.

a) If we neglect the current in feedback

$$\text{resistor: } I_D = 200 \mu\text{A} = \frac{1}{2} K_n \frac{W}{L} V_{ov}^2 = \frac{1}{2} \times 2 \times V_{ov}^2 \Rightarrow$$

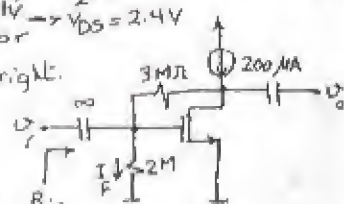
$$V_{ov}^2 = 200 \times 10^{-3} \Rightarrow V_{ov} = 0.45 \text{ V} \Rightarrow V_{GS} = V_t + V_{ov}$$

$$\Rightarrow V_{GS} = 0.5 + 0.45 = 0.95 \text{ V}$$

$$\Rightarrow V_G = 0.95 \text{ V} \Rightarrow I_F = \frac{0.95}{2 \text{ M}} = 0.48 \mu\text{A} \ll 200 \mu\text{A}$$

$$\Rightarrow V_{DS} = 0.48 \times 5 = 2.4 \text{ V} \Rightarrow V_{DS} = 2.4 \text{ V}$$

So our assumption for neglecting I_F was right.



b) To find the small-signal gain we write a KCL

at the output node:

$$\frac{V_o}{r_o} + g_m V_{gs} + \frac{V_o - V_i}{R_F} = 0$$

$$V_{gs} = V_i$$

$$\frac{V_o}{r_o} + g_m V_i + \frac{V_o}{R_F} - \frac{V_i}{R_F} = 0 \Rightarrow \frac{V_o}{V_i} = \frac{\frac{1}{R_F} - g_m}{\frac{1}{r_o} + \frac{1}{R_F}}$$

$$g_m = \frac{2I_D}{V_{ov}} = \frac{2 \times 200 \mu\text{A}}{0.45} = 0.89 \text{ mA/V}$$

$$r_o = \frac{V_A}{I_D} = \frac{20}{0.2} = 100 \text{ k}\Omega$$

$$\frac{V_o}{V_i} = \frac{\frac{1}{3000} - 0.89}{\frac{1}{3000} + \frac{1}{100}} = -86.1 V/V$$

$$V_{DS\min} = V_{GS} - V_t = V_{ov} = 0.45 \text{ V}$$

In our case $V_{DS} = 2.4 \text{ V}$, therefore the largest signal at the output is $2.4 - 0.45 = 1.95 \text{ V}$. The corresponding input signal is

$$\frac{V_o}{A} = \frac{1.95}{-86.1} = -0.023 \text{ V or } 23 \text{ mV.}$$

$$\text{c) } R_{in} = \frac{V_x}{I_x}$$

$$I_x = \frac{V_x}{R_i} + \frac{V_x - V_o}{R_F} \quad (1)$$

$$\frac{V_x - V_o}{R_F} = \frac{V_o}{r_o} + g_m V_x \Rightarrow V_o = V_x \frac{\frac{1}{R_F} - g_m}{\frac{1}{r_o} + \frac{1}{R_F}}$$

$$\text{① } I_x = \frac{V_x}{R_i} + \frac{V_x}{R_F} - \frac{V_x}{R_F} \frac{\frac{1}{R_F} - g_m}{\frac{1}{r_o} + \frac{1}{R_F}}$$

$$\frac{V_x}{I_x} = R_{in} = \frac{1}{\frac{1}{R_i} + \frac{1}{R_F} - \frac{1}{R_F \left(\frac{R_F}{r_o} + 1 \right)} + \frac{g_m}{\left(\frac{R_F}{r_o} + 1 \right)}}$$

$$R_{in} = R_i \parallel R_F \parallel \frac{1 + R_F/r_o}{g_m - 1/R_F}$$

$$R_{in} = 2 \text{ M} \parallel 3 \text{ M} \parallel \frac{1 + 3000/100}{0.89 - 1/3000} = 33.9 \text{ k}\Omega$$

6.58

Refer to Fig. 6.18a and assume Q_2 and Q_3 are matched:

$$K'_n = 2.5 K'_p = 250 \mu\text{A}/\text{V}^2, \quad V_{A_n} = |V_{A_p}| = 10\text{V}$$

$$R_{out} = 100\text{k}\Omega = r_{o1} \parallel r_{o2} = \frac{10}{I_{D1}} \parallel \frac{10}{I_{D2}}$$

$$\text{Since } I_{D1} = I_{D2} \Rightarrow \frac{10}{I_{D1}} = 200 \Rightarrow I_{D1} = I_{D2} = 0.05\text{mA}$$

$$I_{REF} = I_{D2} = 0.05\text{mA}$$

$$\text{Eq. 6.49: } A_v = -g_m (r_{o1} \parallel r_{o2}) \approx -40 = -g_m \times 100\text{k}$$

$$\Rightarrow g_m = 0.4\text{mA/V}$$

$$g_m = \sqrt{2K'_n \left(\frac{W}{L}\right)_1 I_{D1}} \Rightarrow \left(\frac{W}{L}\right)_1 = \frac{0.4^2}{2 \times 250 \times 10^{-3} \times 0.05} = 6.4$$

$$\left(\frac{W}{L}\right)_1 = 6.4$$

$$g_{m1} = \frac{2I_{D1}}{V_{ov1}} \Rightarrow V_{ov1} = \frac{2 \times 0.05}{0.4} = 0.25\text{V}$$

If Q_2 and Q_3 have the same V_{ov} as Q_1 , then

$$|V_{ov2}| = 0.25\text{V}$$

$$I_{D2} = \frac{1}{2} K'_p \left(\frac{W}{L}\right)_2 V_{ov}^2 \Rightarrow \left(\frac{W}{L}\right)_2 = \frac{0.05 \times 2}{100 \times 10^{-3} \times 0.25^2} = 16$$

$$\left(\frac{W}{L}\right)_2 = \left(\frac{W}{L}\right)_3 = 16 \quad (Q_2 \text{ and } Q_3 \text{ are matched})$$

6.59

As discussed in Example 6.8, the transfer characteristic of the amplifier over the desired region (segment III) is quite linear. Therefore the DC bias component of the input signal (for maximum output swing) should be chosen at the midpoint between V_{IA} and V_{IB} that is:

$$\text{input dc bias} = \frac{V_{IA} + V_{IB}}{2} = \frac{0.88 + 0.93}{2} = 0.905\text{V}$$

The corresponding amplitude of the resulting output sinusoid is:

$$\text{output sinusoid amplitude} = \frac{V_{OA} + V_{OB}}{2} = \frac{2.47 + 0.33}{2}$$

$$\text{output sinusoid amplitude} = 1.4\text{V}$$

6.60

As discussed in Example 6.8, the transfer characteristic of the amplifier over the region labeled as segment III, is quite linear.

$$V_{OA} = V_{DD} - V_{OV3} = 5 - 0.53 = 4.47\text{V}$$

Now to find the linear equation for segment III, we can write $i_{D1} = i_{D2}$:

$$\frac{1}{2} K'_n \left(\frac{W}{L}\right)_1 (V_I - V_{tn})^2 \left(1 + \frac{V_{O1}}{V_{A_n}}\right) = \frac{1}{2} K'_p \left(\frac{W}{L}\right)_2 (V_{SG} - |V_{tp}|)^2 \left(1 + \frac{V_{O2}}{V_{A_p}}\right)$$

$$\Rightarrow 200 (V_I - 0.6)^2 \left(1 + \frac{V_{O1}}{20}\right) = 65 \times 0.53^2 \times \left(1 + \frac{V_{DD} - V_{O1}}{10}\right) \left(1 + \frac{V_{DD} - V_{O1}}{V_{A_p}}\right)$$

$$\frac{200}{65 \times 0.53^2} (V_I - 0.6)^2 = \frac{1.5 - V_{O1}/10}{1 + \frac{V_{O1}}{20}}$$

$$7.3 (V_I - 0.6)^2 = \frac{1 - V_{O1}/15}{1 + \frac{V_{O1}}{20}} = \frac{1 - 0.067 V_{O1}}{1 + 0.05 V_{O1}} \approx 1 - 0.117 V_{O1}$$

$$\Rightarrow V_{O1} = 8.57 - 62.57 (V_I - 0.6)^2 \quad (1)$$

If we substitute for $V_{OA} = 4.47\text{V}$, then $V_I = 0.86\text{V}$

To determine coordinates of B, note that

$$V_{GB} - V_{tn} = V_{OB} \quad \text{or} \quad V_{IB} - 0.6 = V_{OB}$$

substitute in (1):

$$V_{OB} = 8.57 - 62.57 (V_{OB} + 0.6)^2 \Rightarrow V_{OB} = 0.36\text{V}$$

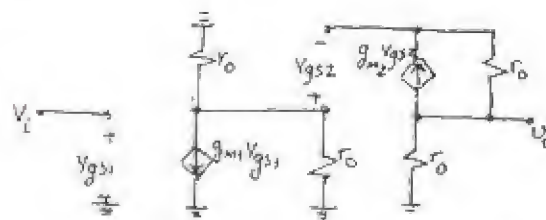
$$V_{GB} = 0.6 + 0.36 = 0.96\text{V}$$

Therefore the linear region is:

$$0.86\text{V} \leq V_I \leq 0.96\text{V} \quad \text{or} \quad 0.36\text{V} \leq V_O \leq 4.47\text{V}$$

6.61

Since $V_{A_n} = |V_{A_p}|$ and the drain current of both Q_1 and Q_2 is equal to I , their output resistances are equal. That is $r_{o1} = r_{o2} = r_o$. The small-signal model of this amplifier is:



Cont.

$$\begin{aligned}
 v_{gs2} &= -g_{m1} v_{gs1} (r_{o1} || r_{o2}) \text{ and } v_{gs1} = v_i \\
 v_{gs2} &= -g_{m1} \frac{r_o}{2} v_i \\
 v_o &= -g_{m2} v_{gs2} (r_{o1} || r_{o2}) = -g_{m2} (-g_{m1} \frac{r_o}{2} v_i) \frac{r_o}{2} \\
 A_v = \frac{v_o}{v_i} &= g_{m1} g_{m2} \frac{r_o^2}{4}
 \end{aligned}$$

6.62

Refer to Fig. 6.18a.

Note that Q_2, Q_3 are not matched.

$$I_{D1} = 100 \mu A$$

$$\begin{aligned}
 a) \quad I_{D2} &= I_{D1} = 100 \mu A \quad \frac{I_{D3}}{I_{D2}} = \frac{(W/L)_3}{(W/L)_2} = \frac{W_3}{W_2} \\
 (\text{Note that } V_{SG2} &= V_{SG3}) \\
 \Rightarrow I_{D3} &= 100 \mu A \quad \frac{10}{40} = 25 \mu A \Rightarrow I_{REF} = 25 \mu A
 \end{aligned}$$

b) By referring to Fig. 6.18d, you notice that in Segment III, both Q_1 and Q_2 are in saturation and the transfer characteristic is quite linear. The output voltage in this segment is limited between V_{OA} and V_{OB} :

$$\begin{aligned}
 \text{Coordinates of point A: } V_{OA} &= V_{DD} - V_{OV3} \\
 V_{OV3}^2 &= \frac{I_{D3}}{\frac{1}{2} K_P (\frac{W}{L})_3} = \frac{25}{\frac{1}{2} \times 50 \times \frac{10}{1}} = 0.1^V = V_{OV3} \Rightarrow 0.32^V
 \end{aligned}$$

$$V_{OA} = 3.3 - 0.32 = 2.98^V$$

$$\text{At point B: } V_{OB} = V_{ISB} - V_{en}$$

Now we find the transfer equation for the linear section: (Refer to Example 6.8)

$$i_{D1} = i_{D2} \Rightarrow \quad (\text{Note that } V_{G2} = V_{G3})$$

$$K'_n (\frac{W}{L})_1 (V_i - V_{tn})^2 (1 + \frac{V_o}{V_{An}}) = K'_p (\frac{W}{L})_2 V_{G3}^2 (1 + \frac{V_{DD} - V_o}{V_{Ap2}})$$

$$100 \times \frac{20}{1} (V_i - 0.8)^2 (1 + \frac{V_o}{100}) = 50 \times \frac{40}{1} \times 0.32^2 (1 + \frac{3.3 - V_o}{50})$$

$$(V_i - 0.8)^2 = 0.32^2 (1.066 - \frac{V_o}{50}) / (1 + \frac{V_o}{100})$$

$$(V_i - 0.8)^2 = 0.11 (\frac{1 - 0.0195 V_o}{1 + 0.01 V_o}) \approx 0.11 (1 - 0.03 V_o)$$

$$(V_i - 0.8)^2 = 0.11 (1 - 0.03 V_o) \quad (1)$$

$$\text{Now if we solve for } V_{OB} = V_{ISB} - 0.8$$

$$V_{OB}^2 + 0.0033 V_{OB} - 0.11 = 0 \Rightarrow V_{OB} = 0.33^V$$

Therefore the extreme values of V_o for which Q_1 and Q_2 are in saturation, 0.33^V to 2.98^V

c) From (b) we can find V_{IA} and V_{IB} :

$$V_{IB} = V_{OB} + V_t = 0.33 + 0.8 = 1.13^V$$

If we solve (1) for $V_{IA} = 2.98^V$ then:

$$(V_{IA} - 0.8)^2 = 0.11 (1 - 0.03 \times 2.98) \Rightarrow V_{IA} = 1.116^V$$

$$\begin{aligned}
 \text{Large-signal voltage gain} &= \frac{\Delta V_o}{\Delta V_i} = \frac{2.98 - 0.33}{1.13 - 1.116} \\
 \frac{\Delta V_o}{\Delta V_i} &= -189.3 \text{ V/V}
 \end{aligned}$$

$$d) \quad V_o = \frac{V_{DD}}{2} = \frac{3.3}{2} = 1.65^V$$

Differentiating both sides of (1): $(\frac{\partial}{\partial V_i})$

$$\begin{aligned}
 2(V_i - 0.8) &= 0.11 \times (-0.03) \frac{\partial V_o}{\partial V_i} \\
 \Rightarrow \frac{\partial V_o}{\partial V_i} &= -606.1 (V_i - 0.8)
 \end{aligned}$$

for $V_o = 1.65^V$, from (1) we have:

$$(V_i - 0.8)^2 = 0.11 (1 - 0.03 \times 1.65) \Rightarrow V_i = 1.12^V$$

$$\left. \frac{\partial V_o}{\partial V_i} \right|_{V_i = 1.12^V} = -195.8 \text{ V/V}$$

$$e) \quad R_{out} = r_{o1} || r_{o2}$$

$$r_{o1} = \frac{V_{An}}{I_{D1}} = \frac{100}{0.1^m} = 1 \text{ M}\Omega$$

$$r_{o2} = \frac{V_{Ap}}{I_{D2}} = \frac{50}{0.1^m} = 500 \text{ k}\Omega \quad \Rightarrow R_{out} = 333$$

$$g_{m1} = \sqrt{2 K'_n (\frac{W}{L})_1 I_{D1}} = \sqrt{2 \times 100 \times \frac{20}{1} \times 100 \mu A} = 0.632 \text{ m}$$

$$A_v = -g_{m1} (r_{o1} || r_{o2}) = -210.6 \text{ V/V}$$

6.63

a) When D and G are open, since the gates don't draw any current, therefore no current through R and $V_D = V_G$, $I_{D1} = I_{D2}$.

$$\frac{1}{2} K'_n (\frac{W}{L})_1 (V_G - 1.5 - 0.5)^2 = \frac{1}{2} K'_p (\frac{W}{L})_2 (1.5 - V_G)^2$$

$$(V_G + 1)^2 = (1 - V_G)^2 \Rightarrow V_G + 1 = 1 - V_G \Rightarrow V_G = 0$$

$$I_{D1} = \frac{1}{2} \times 1 \times (0 + 1.5 - 0.5)^2 = 0.5 \text{ mA}$$

$$I_{D1} = I_{D2} = 0.5 \text{ mA}$$

Cont

$$b) V_o = V_i - R(2g_m V_{gs})$$

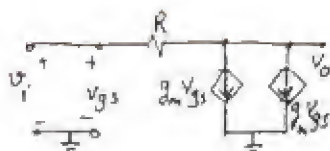
$$V_{gs} = V_i$$

$$V_o = V_i - 2g_m R V_i$$

$$A_v = \frac{V_o}{V_i} = 1 - 2g_m R$$

$$g_m = \frac{2I_D}{V_{GS} - V_t} = \frac{2 \times 0.5}{1.5 - 0.5} = 1 \text{ mA/V}$$

$$A_v = 1 - 2 \times 1 \times 1000 = -1999 \text{ V/V}$$



$$c) r_o = \frac{V_A}{I_D} = \frac{20}{0.5} = 40 \text{ k}\Omega$$

If we write KCL

at D:

$$\frac{V_i - V_o}{R} = 2g_m V_{gs} + \frac{V_o}{r_o/2}, \quad V_{gs} = V_i$$

$$\frac{V_i}{R} - 2g_m V_i = \frac{V_o}{R} + \frac{2V_o}{r_o} \Rightarrow \frac{V_o}{V_i} = A_v = \frac{1 - 2g_m R}{1 + \frac{2R}{r_o}}$$

$$\text{or } A_v = \frac{1 - 2 \times 1 \times 1000}{1 + \frac{2 \times 1000}{40}} = -39.2 \text{ V/V}$$

$$R_{in} = \frac{V_x}{i_x} : V_x - R i_x = \frac{r_o}{2} (i_x - 2g_m V_{gs})$$

$$V_{gs} = V_x$$

$$V_x + 2g_m \frac{r_o}{2} V_x = R i_x + \frac{r_o}{2} i_x \Rightarrow R_{in} = \frac{V_x}{i_x} = \frac{R + r_o/2}{1 + g_m r_o}$$

$$R_{in} = \frac{1000 + 40/2}{1 + 1 \times 40} = 24.9 \approx 25 \text{ k}\Omega$$

$$d) \frac{V_o}{V_{sig}} = A_v \frac{R_{in}}{R_{in} + R_{sig}} = -39.2 \times \frac{25 \text{ k}}{100 \text{ k} + 25 \text{ k}}$$

$$\frac{V_o}{V_{sig}} = -7.84 \text{ V/V}$$

e) In order for both Q_1 and Q_2 to remain in the saturation region:

$$V_{DS} \geq V_{GS} - V_t \Rightarrow V_D + 1.5 \geq V_G + 1.5 - V_t$$

$$\Rightarrow V_D \geq V_G - 0.5$$

$$\text{For } Q_2 : V_{SD} \geq V_{SG} - |V_t| \Rightarrow 1.5 - V_D \geq 1.5 - V_G - 0.5$$

$$\Rightarrow V_D \leq V_G + 0.5$$

In (a) we showed that the gate is at 0 volt,

therefore $V_D \geq -0.5$ and $V_D \leq 0.5$

$$\Rightarrow -0.5 \leq V_D \leq 0.5$$

6.64

$$R_i = r_{\pi} = \frac{\beta}{g_m} = \frac{\beta}{I_C/V_T} = \frac{100 \times 0.025}{1} = 2.5 \text{ k}\Omega$$

$$g_m = \frac{I_C}{V_T} = 40 \text{ mA/V}, \quad r_o = \frac{V_A}{I_C} = 100 \text{ k}\Omega$$

$$A_{vD} = -g_m r_o = -40 \times 100 = -4000 \text{ V/V}$$

$$R_o = r_o = 100 \text{ k}\Omega$$

If R_i is multiplied by 4, since $R_i \propto \frac{1}{I_C}$, then I_C has to be divided by 4: $I_C = \frac{1 \text{ mA}}{4} = 0.25 \text{ mA}$

$$\text{For } I_C = 0.25 \text{ mA: } g_m = \frac{0.25}{0.025} = 10 \text{ mA/V}$$

$$r_o = \frac{V_A}{I_C} = \frac{100}{0.25} = 400 \text{ k}\Omega$$

$$A_{vD} = -10 \times 400 = -4000 \text{ V/V}$$

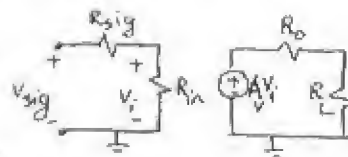
In general $A_{vD} = -g_m r_o = -\frac{I_C}{4} \times \frac{V_A}{I_C} = -\frac{V_A}{4}$ and A_{vD} is not dependent on I_C .

$$R_o = r_o = 400 \text{ k}\Omega, \quad R_i = 4 \times 2.5 = 10 \text{ k}\Omega$$

For $I_C = 1 \text{ mA}$ and $R_{sig} = 5 \text{ k}\Omega$, $R_L = 500 \text{ k}\Omega$

$$V_i = V_{sig} \frac{R_{in}}{R_{in} + R_{sig}}$$

$$G_v = \frac{R_{in}}{R_{in} + R_{sig}} A_{vD} \frac{R_L}{R_L + R_o}$$



$$G_v = -4000 \times \frac{2.5 \text{ k}\Omega}{5 + 2.5} \times \frac{500}{500 + 400} = -1111 \text{ V/V}$$

$$G_v = -1111 \text{ V/V}$$

For $I_C = 0.25 \text{ mA}$: $R_{in} = 10 \text{ k}\Omega$, $R_o = 400$

$$G_v = \frac{10}{10 + 5} \times (-4000) \times \frac{500}{500 + 400} = -1481.5 \text{ V/V}$$

$$G_v = -1481.5 \text{ V/V}$$

6.65

$$a) I_{REF} = I_{C3} = \frac{3 - V_{BE3}}{23k\Omega}$$

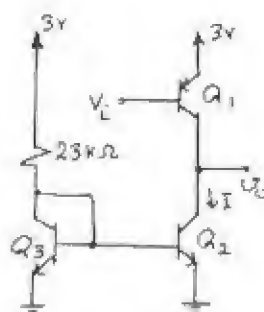
$$I_{REF} = \frac{3 - 0.7}{23} = 0.1 \text{ mA}$$

$$I_{REF} = 0.1 \text{ mA}$$

$$\frac{I_{C2}}{I_{C3}} = \frac{\text{Area of } Q_2}{\text{Area of } Q_3} = 5$$

$$\Rightarrow I_{C2} = 5 I_{C3}$$

$$I_{C2} = I = 0.5 \text{ mA} \Rightarrow I = 0.5 \text{ mA}$$



$$b) |V_A| = 50 \text{ V} \Rightarrow r_{o1} = \frac{|V_A|}{I} = \frac{50}{0.5} = 100 \text{ k}\Omega$$

$$r_{o2} = \frac{50}{0.5} = 100 \text{ k}\Omega$$

Total resistance at the collector of Q_1 is equal to $r_{o1} \parallel r_{o2}$, thus: $r_{\text{tot}} = 100 \text{ k}\Omega \parallel 100 \text{ k}\Omega = 50 \text{ k}\Omega$

$$r_{\text{tot}} = 50 \text{ k}\Omega$$

$$c) g_m = \frac{I_{C1}}{V_T} = \frac{0.5}{0.025} = 20 \text{ mA/V}$$

$$r_{\pi1} = \frac{\beta}{g_m} = \frac{50}{20} = 2.5 \text{ k}\Omega$$

$$d) R_{in} = r_{\pi1} = 2.5 \text{ k}\Omega$$

$$R_o = r_{o1} \parallel r_{o2} = 100 \text{ k}\Omega \parallel 100 \text{ k}\Omega = 50 \text{ k}\Omega$$

$$A_v = -g_m R_o = -20 \times 50 = -1000 \text{ V/V}$$

6.66

$$A_M = -g_m R'_L = -5 \times 20 = -100 \text{ V/V}$$

$$C_{in} = C_{gs} + C_{gd}(1 + g_m R'_L) \quad (\text{Eq. 6.55})$$

$$C_{in} = 2 + 0.1(1 + 5 \times 20) = 12.1 \text{ pF}$$

$$f_H \leq \frac{1}{2\pi C_{in} R_{sig}} \quad (\text{Eq. 6.54})$$

$$f_H \leq \frac{1}{2\pi \times 12.1 \times 10^{-12} \times 20 \times 10^3} = 658 \text{ kHz}$$

6.67

$$\text{Eq. 6.57: } \tau_H = C_{gs} R_{gs} + C_{gd} R_{gd} + C_L R_{L}$$

$$\tau_H = C_{gs} R_{sig} + C_{gd} [R_{sig}(1 + g_m R'_L) + R'_L] + C_L R'_L$$

$$\tau_H = 2 \text{ pF} \times 20 \text{ k}\Omega + 0.1 \text{ pF} [20 \text{ k}\Omega(1 + 5 \times 20) + 20 \text{ k}\Omega] + 1 \text{ pF} \times 20 \text{ k}\Omega$$

$$\tau_H = 264 \text{ ns}$$

$$f_H = \frac{1}{2\pi \tau_H} = 603 \text{ kHz}$$

$$A_M = -g_m R'_L = -5 \times 20 = -100 \text{ V/V}$$

$$\tau_{gs} : 15.1\%$$

$$\tau_{gd} : 77.3\%$$

$$\tau_L : 7.6\%$$

Contribution of each time-constant to the overall τ_H .

If we compare f_H to the one obtained in Problem 6.66, we notice that Problem 6.66 has a larger f_H due to neglecting the time constants of C_L and C_{gs} .

6.68

From Eq. 6.60 we have: $\omega_z = g_m / C_{gd}$

$$\Rightarrow f_z = \frac{g_m}{2\pi C_{gd}} = \frac{5 \text{ m}}{2\pi \times 0.1 \text{ pF}} = 7.96 \text{ GHz}$$

f_{p1} and f_{p2} are the poles of the transfer function of equation (6.60), whose denominator is a quadratic polynomial with coefficients:

$$\begin{aligned} &= [C_{gs} + C_{gd}(1 + g_m R'_L)] R_{sig} + (C_L + C_{gd}) R'_L \\ &= [2 + 0.1(1 + 5 \times 20)] 20 + (1 + 0.1) \times 20 \\ &= 264 \text{ ns} = 264 \times 10^{-9} \text{ sec} \end{aligned}$$

Coefficient of s^2 :

$$\begin{aligned} &= [C_L + C_{gd}] C_{gs} + C_L C_{gd} \\ &= [(1 + 0.1) 2 + 1 \times 0.1] 20 \times 20 \times 10^{-18} \\ &= 920 \times 10^{-18} (\text{sec})^2 \end{aligned}$$

Therefore the quadratic equation is:

$$1 + 264 \times 10^{-9} s + 920 \times 10^{-18} s^2 = 0$$

Denoting the frequencies of the roots of this equation with ω_{p1} and ω_{p2} , we have:

$$\omega_{p1} = 3.84 \times 10^6 \text{ rad/s} \Rightarrow f_{p1} = \frac{\omega_{p1}}{2\pi} = 61.15 \text{ kHz}$$

$$\omega_{p2} = 283.12 \times 10^6 \text{ rad/s} \Rightarrow f_{p2} = \frac{\omega_{p2}}{2\pi} = 45.06 \text{ MHz}$$

Cont.

Since $f_{p1} \ll f_{p2}$ and $f_{p1} \ll f_z$, a good estimate for f_H is f_{p1} :

$$f_H \approx f_{p1} = 611.15 \text{ KHz}$$

Approximate value of f_{p1} obtained using (Eq. 6.66) is:

$$f_{p1} \approx \frac{1}{2\pi[(C_{gs} + C_{gd}(1 + g_m R'_L))R_{sig} + (C_L + C_{gd})R'_L]}$$

$$f_{p1} \approx 603.16 \text{ KHz}$$

Approximate value of f_{p2} obtained using (Eq. 6.67) is:

$$f_{p2} = \frac{[C_{gs} + C_{gd}(1 + g_m R'_L)]R_{sig} + (C_L + C_{gd})R'_L}{2\pi[(C_L + C_{gd})C_{gs} + C_L C_{gd}]R'_L R_{sig}}$$

$$f_{p2} = 4567 \text{ MHz}$$

The estimate of f_{p1} using Eq. 6.66 is 1.3% lower than the exact value, while the estimate of f_{p2} is about 1.3% higher than its exact value.

6.69

$$R'_L = 5 \text{ k}\Omega$$

$$A_M = -g_m R'_L = -5 \times 5 = -25 \text{ V/V}$$

Using (Eq. 6.66):

$$f_{p1} \approx \frac{1}{2\pi[(C_{gs} + C_{gd}(1 + g_m R'_L))R_{sig} + (C_L + C_{gd})R'_L]}$$

$$f_{p1} = \frac{1}{2\pi[(2 + 0.1(1 + 5 \times 5))20 + (1 + 0.1) \times 5]}$$

$$f_{p1} = 1.63 \text{ MHz}$$

Using (Eq. 6.67):

$$f_{p2} = \frac{[C_{gs} + C_{gd}(1 + g_m R'_L)]R_{sig} + (C_L + C_{gd})R'_L}{[C_L + C_{gd}]C_{gs} + C_L C_{gd}]R'_L R_{sig} \times 2\pi}$$

$$f_{p2} = \frac{(2 + 0.1(1 + 5 \times 5))20 + (1 + 0.1) \times 5}{(1 + 0.1) \times 2 + 1 \times 0.1} \times 5 \times 20 \times 2\pi$$

$$f_{p2} = 67.5 \text{ MHz}$$

$$\text{Eq. 6.63: } S_2 = \frac{g_m}{C_{gd}} \Rightarrow f_z = \frac{g_m}{2\pi C_{gd}} = \frac{5 \text{ m}}{2\pi \times 0.1 \text{ pF}} = 7.96 \text{ GHz}$$

$f_{p1} \ll f_{p2}$ and $f_{p1} \ll f_z \Rightarrow f_{p1}$ is the dominant pole.

$$f_H \approx f_{p1} = 1.63 \text{ MHz}$$

$$\text{Gain} \times \text{Bandwidth} = 25 \times 1.63 = 40.75 \text{ MHz}$$

$$f_L = |A_M| f_H = 40.75 \text{ MHz}$$

Since $f_{p1} \ll f_{p2}$ and $f_{p1} \ll f_z$, a dominant pole exists.

$$R'_L = 10 \text{ k}\Omega$$

$$A_M = -5 \times 10 = -50 \text{ V/V}$$

$$f_{p1} = \frac{1}{2\pi[(2 + 0.1(1 + 5 \times 10))20 + (1 + 0.1) \times 10]} = 1.04 \text{ MHz}$$

$$f_{p2} = \frac{(2 + 0.1(1 + 5 \times 10))20 + (1 + 0.1) \times 10}{[(1 + 0.1) \times 2 + 1 \times 0.1] \times 10 \times 20 \times 2\pi}$$

$$f_z = \frac{5}{2\pi \times 0.1} = 7.96 \text{ MHz}$$

$f_{p1} \ll f_{p2}$, $f_{p1} \ll f_z \Rightarrow f_{p1}$ is the dominant pole and therefore $f_H \approx f_{p1} = 1.04 \text{ MHz}$

$$|A_M| \cdot f_H = 50 \times 1.04 = 52 \text{ MHz}$$

Since f_{p2} is still slightly greater than $|A_M| \cdot f_H$, therefore:

$$R'_L = 20 \text{ k}\Omega$$

$A_M = -5 \times 20 = -100 \text{ V/V}$, from Problem 6.68, we have:

$$f_{p1} = 603.16 \text{ KHz}$$

$$f_{p2} = 4567 \text{ MHz}$$

$$f_z = 7.96 \text{ MHz}$$

Again $f_{p1} \ll f_{p2}$ and $f_{p1} \ll f_z$, therefore f_{p1} is the dominant pole and f_H can be approximated by f_{p1} . $f_H \approx f_{p1} = 603.16 \text{ KHz}$

$$|A_M| \cdot f_H = 60.32 \text{ MHz}$$

Since $f_{p2} < |A_M| \cdot f_H$, therefore f_{p2} is smaller than $|A_M| \cdot f_H$

The results are summarized in this table:

R'_L	5 k Ω	10 k Ω	20 k Ω
$A_M \text{ (V/V)}$	-25	-50	-100
$f_{p1} \text{ (MHz)}$	1.63	1.04	0.60
$ A_M \cdot f_H \text{ (MHz)}$	40.75	52.00	60.32

6.70

Using Eq. 6.70: $A_M = -\frac{r_{\pi}}{R_{sig} + r_x + r_{\pi}} (g_m R'_L)$

$r_{\pi} = \frac{\beta}{g_m} = \frac{100}{20} = 5 \text{ k}\Omega \Rightarrow A_M = -\frac{5}{1 + 0.2 + 5} (20 \times 5)$

$A_M = 80.65 \text{ V/V}$

Using Miller's Theorem and Eq. 6.71:

$C_{in} = C_{\pi} + C_{\mu}(1 + g_m R'_L) = 10 + 0.5(1 + 20 \times 5) = 60.5 \text{ pF}$

Eq. 6.69: $R'_{sig} = r_{\pi} \parallel (R_{sig} + r_x) = 5 \text{ k} \parallel (1 \text{ k} + 0.2)$

$R'_{sig} = 0.97 \text{ k}\Omega$

Eq. 6.72: $f_H \approx \frac{1}{2\pi C_{in} R'_{sig}} = \frac{1}{2\pi \times 60.5 \times 0.97 \text{ k}} \Rightarrow$

$f_H = 2.71 \text{ MHz}$

6.71

From Problem 6.70 we have: $r_{\pi} = 5 \text{ k}\Omega$ and

$A_M = -80.65 \text{ V/V}$, $R'_{sig} = 0.97 \text{ k}\Omega$

Eq. 6.75: $f_2 = \frac{g_m}{2\pi C_{\mu}} = \frac{20 \text{ m}}{2\pi \times 0.5 \text{ p}} = 6.37 \text{ GHz}$

Eq. 6.76: $f_{P1} \approx \frac{1}{2\pi [(C_{\pi} + C_{\mu}(1 + g_m R'_L)) R'_{sig} + (C_L + C_{\mu}) R'_L]}$

$f_{P1} \approx \frac{1}{2\pi [(10 + 0.5(1 + 20 \times 5)) 0.97 + 2.5 \times 5]}$

$f_{P1} = 2.24 \text{ MHz}$

Eq. 6.77: $f_{P2} = \frac{(C_{\pi} + C_{\mu}(1 + g_m R'_L)) R'_{sig} + (C_L + C_{\mu}) R'_L}{2\pi [C_{\pi}(C_L + C_{\mu}) + C_L C_{\mu}] R'_{sig} R'_L}$

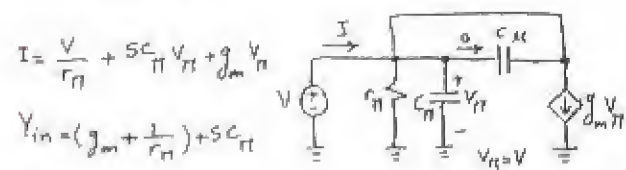
$f_{P2} = \frac{(10 + 0.5(1 + 20 \times 5)) 0.97 + 2.5 \times 5}{2\pi (10(2 + 0.5) + 2 \times 0.5) 0.97 \times 5}$

$f_{P2} = 89.89 \text{ MHz}$

Since $f_{P1} \ll f_{P2}$ and $f_{P1} \ll f_2$, we can approximate f_H by f_{P1} : $f_H \approx f_{P1} = 2.24 \text{ MHz}$

If we compare f_H to the results obtained from applying Miller's Theorem in Problem 6.70, then our results are 17% lower.

6.72



$Z_i = \frac{1}{(g_m + \frac{1}{r_{\pi}}) + 5C_{\pi}} = \frac{1}{\frac{1}{r_e} + 5C_{\pi}} = \frac{r_e}{1 + 5C_{\pi} r_e}$

$Z_i = \frac{r_e}{1 + 5C_{\pi} r_e}$

$f_T = \frac{g_m}{2\pi(C_{\pi} + C_{\mu})}$ Since $C_{\pi} = C_{de} + C_{je} = \frac{I}{I_s} C_{je} + C_{je}$

Therefore C_{π} has a component that depends on the bias current and at high currents $C_{\pi} \gg C_{je}$

and $f \approx \frac{g_m}{r} = \frac{1}{2\pi C_{\pi} r_e}$

Thus: $Z_i \approx \frac{r_e}{1 + \frac{I}{I_s}}$ at high currents

The phase angle will be -45° at $\omega\omega_T$ or

$f = f_T = 400 \text{ MHz}$

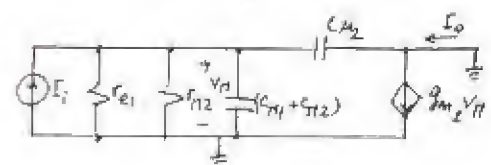
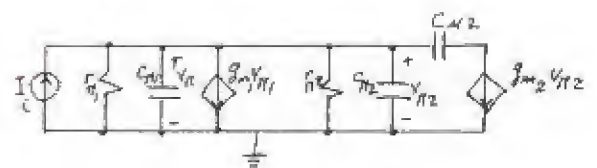
For lower bias currents, so that $C_{\pi} = C_{je}$

$f_T = \frac{1}{4\pi C_{je} r_e}$ and $Z_i = \frac{r_e}{1 + \frac{I}{I_s}}$ and -45°

phase is obtained at $\omega = 2\omega_T$ or $f = 2f_T = 800 \text{ MHz}$

(Assuming that f_T remains constant which is not necessarily true!!)

6.73



$V_{\pi} = \frac{I_i}{(\frac{1}{r_{\pi 1}} + \frac{1}{r_{\pi 2}}) + 5(C_{\pi 1} + C_{\pi 2} + C_{\mu 2})}$

Cont.

$$I_o = g_{m2} V_{\pi} - C_{\mu} S V_{\pi} = \frac{(g_{m2} - S C_{\mu}) I_i}{\left(\frac{1}{r_{\pi 1}} + \frac{1}{r_{\pi 2}}\right) + S(C_{\pi 1} + C_{\pi 2} + C_{\mu 2})}$$

$$\frac{I_o}{I_i} = \frac{g_{m2} - S C_{\mu}}{\left(\frac{1}{r_{\pi 1}} + \frac{1}{r_{\pi 2}}\right) + S(C_{\pi 1} + C_{\pi 2} + C_{\mu 2})}$$

$$I_{C1} = I_{C2} \Rightarrow r_{\pi 1} = r_{\pi 2}, g_{m1} = g_{m2}, C_{\pi 1} = C_{\pi 2}$$

$$\frac{I_o}{I_i} = \frac{g_m - S C_{\mu}}{\left(\frac{1}{r_e} + \frac{1}{r_{\pi}}\right) + (C_{\mu} + 2C_{\pi})S} = \frac{1 - \frac{C_{\mu}}{g_m} S}{\left(\frac{1}{2r_e} + \frac{1}{g_m r_{\pi}}\right) + S \frac{C_{\mu} + 2C_{\pi}}{g_m}}$$

$$g_m r_e = \frac{I_o}{I_i} \frac{V_T}{I_E} = \alpha = \frac{\beta}{\beta + 1}$$

$$g_m r_{\pi} = \beta$$

$$\Rightarrow \frac{I_o}{I_i} = \frac{1 - \frac{C_{\mu}}{g_m} S}{1 + \frac{1}{\beta} + \frac{1}{\beta} + S(2C_{\pi} + C_{\mu})/g_m}$$

$$\frac{I_o}{I_i} = \frac{1}{1 + \frac{2}{\beta}} \frac{1 - S \frac{C_{\mu}}{g_m}}{1 + S(2C_{\pi} + C_{\mu})/g_m(1 + \frac{2}{\beta})}$$

If the circuit is biased at 1mA and $\beta = \infty$,

$$f_T = 400 \text{ MHz and } C_{\mu} = 2 \text{ pF};$$

$$g_m = \frac{I}{0.025} = 40 \text{ mA/V}$$

$$f_T = \frac{g_m}{2\pi(C_{\pi} + C_{\mu})} \Rightarrow C_{\pi} + C_{\mu} = \frac{40 \text{ m}}{2\pi \times 400 \text{ M}} = 15.9 \text{ pF}$$

$$C_{\pi} = 15.9 - 2 = 13.9 \text{ pF}$$

$$\text{Pole Frequency: } f_p = \frac{g_m}{2\pi(2C_{\pi} + C_{\mu})} = \frac{40 \times 10^{-3}}{2\pi(2 \times 13.9 + 2)} \text{ Hz}$$

$$f_p = 213.74 \text{ MHz}$$

$$\text{Zero Frequency: } f_z = \frac{g_m}{2\pi C_{\mu}} = \frac{40 \text{ m}}{2\pi \times 2 \text{ p}} = 3.18 \text{ GHz}$$

6.74

$$A_M = -g_m R'_L = -5 \times 20 = -100 \text{ V/V}$$

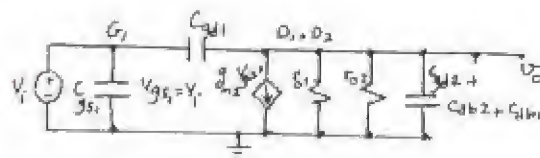
$$f_H = \frac{1}{2\pi(C_L + C_{gd})R'_L} = \frac{1}{2\pi(1 + 0.1) \times 20} = 7.23 \text{ MHz}$$

(Note that in this case there is no R_{sig} and we used Eq. 6.79)

$$f_{3dB} = f_H = 7.23 \text{ MHz}$$

$$f_L = |A_M| \cdot f_H = 723 \text{ MHz}$$

6.75



$$g_m = \sqrt{2\mu_n C_{ox} \frac{W}{L} I_D} = \sqrt{2 \times 90 \times 100 \times 100} = 1060 \text{ mA/V}$$

$$g_m = 1.06 \text{ mA/V}$$

$$r_{o1} = \frac{V_{A1}}{I_{D1}} = \frac{12.8}{0.1} = 128 \text{ k}\Omega$$

$$r_{o2} = \frac{V_{A2}}{I_{D2}} = \frac{10.2}{0.1} = 102 \text{ k}\Omega$$

$$\text{DC-gain} = -g_m(r_{o1} || r_{o2}) = -1.06 \times (128 || 102) = -81.4 \text{ V/V}$$

Total capacitance between output node and ground

$$= C_{gd2} + C_{db1} + C_{db2} = 0.015 + 0.020 + 0.036$$

$$C_L = 0.071 \text{ pF}$$

Write a KCL at output:

$$S C_{gd1}(V_i - V_o) = g_m V_i + \frac{V_o}{r_{o1}} + \frac{V_o}{r_{o2}} + \frac{V_o}{S} S C_L$$

$$\frac{V_o}{V_i} = -\frac{g_m - S C_{gd1}}{\frac{1}{r_{o1}} + \frac{1}{r_{o2}} + (C_L + C_{gd1})S}$$

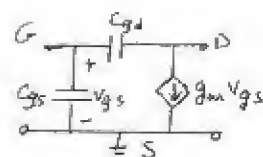
$$\text{Thus: } f_z = \frac{g_m}{2\pi C_{gd1}} = \frac{1.06 \text{ m}}{2\pi \times 0.015 \text{ p}} = 11.3 \text{ GHz}$$

$$f_p = \frac{1}{2\pi} \frac{\frac{1}{r_{o1}} + \frac{1}{r_{o2}}}{C_L + C_{gd1}} = \frac{\frac{1}{128 \text{ k}} + \frac{1}{102 \text{ k}}}{2\pi(0.031 + 0.015) \text{ p}} \text{ Hz}$$

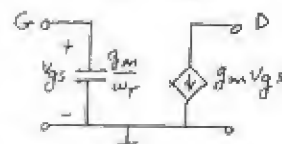
$$f_p = 24.1 \text{ MHz}$$

6.76

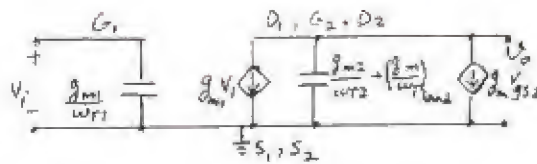
a) For small C_{gd} and low gain from G to D, we can neglect the miller effect and C_{gd} .



$$\omega_T = \frac{g_m}{C_{gs} + C_{gd}} \approx \frac{g_m}{C_{gs}} \quad \text{Thus } C_{gs} = \frac{g_m}{\omega_T}$$



b) replace the controlled source $g_{m2} V_{gs2}$ with a resistance $\frac{1}{g_{m2}}$. (source absorption theory) Cont.



$$V_o = -g_{m1} V_i \frac{1}{g_{m2} + s \left(\frac{g_{m2}}{\omega_{T2}} + \frac{g_{mload}}{\omega_{Tload}} \right)}$$

Since the load device is identical to Q_1 ,
 $g_{mload} = g_{m1}$ and $\omega_{Tload} = \omega_{T1} = \omega_T$.

Thus:

$$\frac{V_o}{V_i} = \frac{-g_{m1}/g_{m2}}{1 + \frac{s}{\omega_T} \left(1 + \frac{g_{m1}}{g_{m2}} \right)}$$

$$\frac{g_{m1}}{g_{m2}} = \frac{A_n C_{ox} \left(\frac{W_1}{L_1} \right) V_{ov}}{A_n C_{ox} \left(\frac{W_2}{L_2} \right) V_{ov}} = \frac{W_1}{W_2}$$

$$\Rightarrow \frac{V_o}{V_i} = \frac{-A_o}{1 + \frac{s}{\omega_T} (1 + A_o)} \quad \text{where } A_o = \frac{W_1}{W_2} = \frac{g_{m1}}{g_{m2}}$$

c) $A_o = 3 \text{ V/V}$, $W_2 = 25 \mu\text{m}$

$$A_o = \frac{W_1}{W_2} \Rightarrow W_1 = 3 \times 25 = 75 \mu\text{m}$$

$$I_{D1} = \frac{1}{2} \mu_n C_{ox} \frac{W_1}{L_1} (V_{G1} - V_t)^2 = \frac{1}{2} \times 200 \times \frac{75}{0.5} \times 0.3^2$$

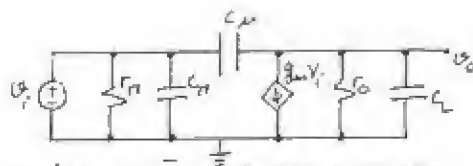
$$I_{D1} = 1.35 \text{ mA}$$

$$I_{D2} = \frac{1}{2} \times 200 \mu\text{A/V}^2 \times \frac{25}{0.5} \times 0.3^2 = 0.45 \text{ mA}$$

$$\text{Thus: } I = I_{D1} + I_{D2} = 1.35 + 0.45 = 1.8 \text{ mA}$$

$$f_{3db} = \frac{f_T}{1 + A_o} = \frac{12 \times 10^7}{1 + 3} = 36 \text{ Hz}$$

6.77



writing a node equation at the output yields:

$$sC_L(V_i - V_o) = g_m V_i + \frac{V_o}{r_o} + \frac{V_o}{r_o} C_L s$$

$$\frac{V_o}{V_i} = \frac{C_L s - g_m}{\frac{1}{r_o} + (C_L + C_{gs})s} = -g_m r_o \frac{1 - sC_L/g_m}{1 + s(C_L + C_{gs})r_o}$$

for small $C_L, \omega C_L \ll g_m$: $\frac{V_o}{V_i} = \frac{-g_m r_o}{1 + s(C_L + C_{gs})r_o}$

For $I_C = 200 \mu\text{A}$, $V_A = 100 \text{ V}$: $g_m = \frac{200 \mu\text{A}}{0.025} = 8 \text{ mA/V}$
 $r_o = \frac{100}{200} = 0.5 \text{ M}\Omega$

Thus DC-Gain = $-g_m r_o = -8 \times 0.5 \times 10^3 = -4000 \text{ V/V}$

For $C_L = 1 \text{ pF}$, $C_{gs} = 0.2 \text{ pF}$:

$$\omega_{3db} = \frac{1}{(C_L + C_{gs})r_o} = \frac{1}{(1 + 0.2) \times 10^{-12} \times 0.5 \times 10^6} = 1.67 \text{ Mrad/s}$$

$$f_{3db} = 265.4 \text{ kHz} = f_H$$

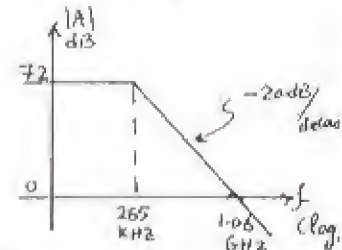
$$f_T = |A_o| f_H = 4000 \times 265.4 = 1.06 \text{ GHz}$$

Bode Plot for $|A|$:

$$4000 \text{ V/V} = 72 \text{ dB}$$

Check $f_T = \frac{g_m}{2\pi C_{gs}}$

$$f_T = \frac{8 \text{ m}}{2\pi \times 0.2 \text{ p}} = 6.4 \text{ GHz}$$



6.78

$$f_T = \frac{g_m}{2\pi(C_L + C_{gd})} \quad g_m = 1 \text{ mA/V}, f_T = 26 \text{ GHz}$$

$$\Rightarrow C_L + C_{gd} = \frac{1 \times 10^{-3}}{2\pi \times 26 \times 10^9} = 79.61 \text{ fF}$$

To have $f_{T2} = 1 \text{ GHz}$, we need:

$$C_L + C_{gd} = \frac{1 \times 10^{-3}}{2\pi \times 1 \times 10^9} = 159.23 \text{ fF}$$

Thus we need an additional capacitance of

$$159.23 - 79.61 = 79.61 \text{ fF}$$

6.79

$$g_m = \sqrt{2\mu_n \frac{W}{L} I_D} = \sqrt{2 \times 160 \times \frac{50}{0.5} \times 0.5} = 4 \text{ mA/V}$$

$$g_{mb} = \chi g_m = 0.2 \times 4 = 0.8 \text{ mA/V}$$

$$r_o = \frac{V_A}{I_D} = \frac{1}{\lambda I_D} = \frac{1}{0.1 \times 0.5} = 20 \text{ k}\Omega$$

$$R_o = r_o = 20 \text{ k}\Omega$$

$$A_{v0} = 1 + (g_m + g_{mb})r_o = 1 + (4 + 0.8) \times 20 \text{ k} = 97 \text{ V/V}$$

$$R_{out} = r_o + A_{v0} R_s \quad (\text{Eq. 6.102})$$

$$R_{out} = 20 \text{ k} + 97 \times 20 \text{ k} = 1.96 \text{ M}\Omega$$

$$R_{in} = \frac{r_o + R_L}{A_{v0}} \quad (\text{Eq. 6.86})$$

$$R_{in} = \frac{20 + 20}{97} = 0.41 \text{ k}\Omega$$

$$A_v = A_{v0} \frac{R_L}{R_L + r_o} = 97 \frac{20}{20 + 20} = 48.5 \text{ V/V}$$

Cont.

$$G_v = \frac{V_o}{V_{s,ig}} = A_{v_o} \frac{R_L}{R_L + r_o + A_{v_o} R_s} \quad (\text{Eq. 6.95})$$

$$G_v = \frac{97 \times 20^k}{20^k + 20^k + 97 \times 20^k} = 0.98 \text{ V/V}$$

$$G_{is} = A_{v_o} \frac{R_s}{R_{out}} = 97 \times \frac{20}{1960} = 0.99 \text{ A/A}$$

$$G_i = G_{is} \frac{R_{out}}{R_{out} + R_i} = 0.99 \times \frac{1960}{1960 + 20} = 0.98 \text{ A/A}$$

6.80

$$R_L = r_o$$

$$A_v = 100 \text{ V/V} = \frac{V_o}{V_i} = A_{v_o} \frac{R_L}{R_L + r_o} = A_{v_o} \frac{r_o}{r_o + r_o}$$

$$\Rightarrow A_v = A_{v_o} / 2 = 100 \Rightarrow A_{v_o} = 200 \text{ V/V}$$

$$R_{in} = 2 \text{ k}\Omega$$

$$R_{in} = \frac{r_o + R_L}{A_{v_o}} = \frac{r_o + r_o}{A_{v_o}} \Rightarrow 2^k = \frac{2r_o}{200} \Rightarrow r_o = 100 \text{ k}\Omega$$

$$r_o = \frac{V_A}{I_D} \Rightarrow I_D = \frac{V_A}{r_o} = \frac{20}{100} = 0.2 \text{ mA}$$

$$A_{v_o} = 1 + (g_m + g_{mb}) r_o = 1 + (1 + \chi) g_m r_o$$

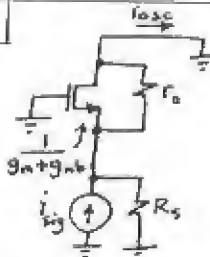
$$200 = 1 + (1 + 0.2) g_m \times 100 \Rightarrow g_m = 1.66 \text{ mA/V}$$

$$g_m = \frac{2I_D}{V_{ov}} \Rightarrow V_{ov} = \frac{2 \times 0.2}{1.67} = 0.24 \text{ V}$$

$$I_D = \frac{1}{2} \mu_n \frac{W}{L} \frac{V_{ov}^2}{V_{ov}} \Rightarrow \frac{W}{L} = \frac{2I_D}{\mu_n V_{ov}^2} = \frac{2 \times 0.2}{0.1 \times 0.24^2}$$

$$\frac{W}{L} = 69.4$$

6.81



$$i_{osc} = \frac{R_s i_{sig}}{R_s + (r_o \parallel \frac{1}{g_m + g_{mb}})} = \frac{R_s}{R_s + \frac{r_o}{1 + (g_m + g_{mb}) r_o}} i_{sig}$$

$$G_{is} = \frac{i_{osc}}{i_{sig}} = \frac{R_s}{R_s + \frac{r_o}{A_{v_o}}} = \frac{A_{v_o} R_s}{r_o + A_{v_o} R_s}$$

Using (6.102) we have: $G_{is} = \frac{A_{v_o} R_s}{R_{out}}$

If $A_{v_o} R_s \gg r_o$ that is $[1 + (g_m + g_{mb}) r_o] R_s \gg r_o$

or $(g_m + g_{mb}) R_s \gg 1$ then $G_{is} \approx 1$

6.82

$$R_{in} = \frac{r_o + R_L}{A_{v_o}}, \quad A_{v_o} = 1 + (g_m + g_{mb}) r_o$$

$$\Rightarrow R_{in} = \frac{1}{g_m + g_{mb}} + \frac{R_L}{A_o}$$

If $R_L = A_o r_o$ then $R_{in} = \frac{1}{g_m + g_{mb}} + r_o$

6.83

$$g_m = \frac{2I_D}{V_{ov}} = \frac{2 \times 1^m}{0.8 - 0.55} = 8 \text{ mA/V}$$

$$g_{mb} = \chi g_m = 0.2 \times 8 = 1.6 \text{ mA/V}$$

$$r_o = \frac{V_A}{I_D} = \frac{20}{1^m} = 20 \text{ k}\Omega$$

From Eq. 6.101 we have: $R_{out} = r_o + [1 + (g_m + g_{mb}) r_o] R_s$

$$R_{out} = 20 + (1 + (8 + 1.6) \times 20) R_s = 200 \text{ k}\Omega$$

$$R_s = 932.64 \Omega$$

$$V_{BIAS} = I_D R_s + V_{GS} = 1^m \times 932.64 \times 10^{-3} + 0.8 = 1.73 \text{ V}$$

$$V_{BIAS} = 1.73 \text{ V}$$

6.84

$$V_s + (g_m + g_{mb}) V_o = i_{osc} - \frac{V_o}{r_o}$$

$$\Rightarrow i_{osc} = V_s \left(\frac{1}{r_o} + g_m + g_{mb} \right) \quad (1)$$

$$V_s = V_{sig} - R_s i_{osc}$$

If we substitute V_s in (1):

$$i_{osc} = (V_{sig} - R_s i_{osc}) \left(\frac{1}{r_o} + g_m + g_{mb} \right)$$

$$i_{osc} \left(1 + \frac{R_s}{r_o} + R_s (g_m + g_{mb}) \right) = V_{sig} \frac{(1 + (g_m + g_{mb}) r_o)}{r_o}$$

$$i_{osc} = V_{sig} \frac{1 + (g_m + g_{mb}) r_o}{r_o + R_s + R_s r_o (g_m + g_{mb})}$$

Since $A_{v_o} = G_{v_o} = 1 + (g_m + g_{mb}) r_o$ (Eq. 6.88)

and $R_{out} = r_o + A_{v_o} R_s$ (Eq. 6.102), then

$$i_{osc} = V_{sig} \frac{A_{v_o}}{R_{out}}$$

6.85

$$a) V_{GS2} = V_{GS3} \Rightarrow I_{D2} = I_{D3} \quad \text{Also } I_{D1} = I_{D2}$$

$$\Rightarrow I_{D1} = 100 \mu A$$

$$I_{D1} = \frac{1}{2} K_n \frac{W}{L} (V_{GS1} - V_t)^2 \Rightarrow 0.1 = \frac{1}{2} \times 4 \times (V_{GS1} - 0.8)^2$$

$$V_{GS1} - 0.8 = 0.224 \Rightarrow V_{GS1} = 1.024 V, \quad V_{GS1} = V_{GS2} = V_{GS3} = 1.024 V$$

$$V_{BIAS} = R_S I_{D1} + V_{GS} = 0.05 \times 0.1 + 1.024 = 1.029 V$$

$$b) g_{m1} = \frac{2I_{D1}}{V_{OV}} = \frac{0.1 \times 2}{0.224} = 0.89 \text{ mA/V}$$

$$g_{m2} = \sqrt{2K_n \frac{W}{L} I_{D2}} = \sqrt{2 \times 4 \times 0.1} = 0.89 \text{ mA/V}$$

$$g_{m3} = g_{m2} = 0.89 \text{ mA/V}$$

$$g_{mb} = \chi g_m \Rightarrow g_{mb1} = g_{mb2} = g_{mb3} = 0.2 \times 0.89 = 0.18 \text{ mA/V}$$

$$r_{D1} = r_{D2} = r_{D3} = \frac{V_A}{I_D} = \frac{20}{0.1} = 200 \text{ k}\Omega$$

$$c) R_{in} = \frac{r_o + R_L}{A_{v0}} \quad \text{where } A_{v0} = 1 + (g_{m1} + g_{mb1}) r_o$$

$$A_{v0} = 1 + (0.89 + 0.18) 200$$

$$A_{v0} = 215 \text{ V/V}$$

In this case R_L is in fact R_{out} of the Active load in the drain of Q_1 , which is $r_{D2} = 200 \text{ k}\Omega$.

$$\text{Thus: } R_{in} = \frac{200 + 200}{215} = 1.86 \text{ k}\Omega$$

$$d) R_{out} = r_o + A_{v0} R_S = 200 + 215 \times 0.05 = 210.75 \text{ k}\Omega$$

$$e) A_v = \frac{V_o}{V_i} = A_{v0} \frac{R_L}{R_L + r_o} = 215 \frac{200}{200 + 200} = 107.5 \text{ V/V}$$

$$G_v = A_{v0} \frac{R_L}{R_L + R_{out}} = 215 \frac{200}{200 + 210.75} = 104.7 \text{ V/V}$$

f) For Q_2 to stay in saturation region, V_o can go as high as $V_{DD} - V_{ov2}$, Thus $V_o \leq 3.3 - 0.224$ or $V_o \leq 3.076 \text{ V}$.

For Q_1 to stay in saturation region, we need to have $V_{GS1} < V_t \Rightarrow V_{BIAS} - V_o < 0.8 \Rightarrow$

$$V_o \geq 1.029 - 0.8 \text{ or } V_o \geq 0.229 \text{ V}$$

hence $0.229 \text{ V} \leq V_o \leq 3.076 \text{ V}$. This implies that the peak-to-peak output swing is

$$3.076 - 0.229 = 2.847 \text{ V}$$

Since $G_v = \frac{V_o}{V_{sig}} = 104.7$, then the maximum

peak-to-peak value of V_{sig} is $\frac{2.847}{104.7}$

that is 27 mV.

6.86

From Fig. 6.31b the low-frequency gain $\frac{V_o}{V_{sig}}$ can be written as:

$$\frac{V_o}{V_{sig}} = \frac{1}{R_S + \frac{1}{g_m + g_{mb}}} \times (g_m + g_{mb}) \times R'_L$$

$$\frac{V_o}{V_{sig}} = \frac{(g_m + g_{mb}) R'_L}{1 + (g_m + g_{mb}) R_{sig}} = \frac{(5 + 0.2 \times 5) \times 20}{1 + (5 + 0.2 \times 5) \times 1} = 17.14 \text{ V/V}$$

$$\frac{V_o}{V_{sig}} = 17.14 \text{ V/V}$$

From Eq. 6.105 we have $f_{P1} = \frac{1}{2\pi C_{gs} (R_S \parallel \frac{1}{g_m + g_{mb}})}$

$$f_{P1} = \frac{1}{2\pi \times 2 \text{ pF} (1 \text{ k}\Omega \parallel \frac{1}{5 + 0.2 \times 5})} = 557 \text{ MHz}$$

From Eq. 6.106 we have:

$$f_{P2} = \frac{1}{2\pi (C_{gd} + C_L) R'_L} = \frac{1}{2\pi (0.1 + 2) 20 \text{ k}} = 3.79 \text{ MHz}$$

Since $f_{P2} \ll f_{P1}$, then f_{P2} is the dominant pole and

$$f_H = f_{P2} = 3.79 \text{ MHz}$$

6.87

$$A_{v0} = 1 + (g_m + g_{mb}) r_o = 1 + (5 + 0.2 \times 5) 20 \text{ k} = 121 \text{ V/V}$$

$$R_{out} = r_o + A_{v0} R_S = 20 + 121 \times 1 = 141 \text{ k}\Omega$$

$$G_v = G_{v0} \frac{R_L}{R_L + R_{out}} = A_{v0} \frac{R_L}{R_L + R_{out}} = 121 \frac{20 \text{ k}}{20 \text{ k} + 141 \text{ k}}$$

$$G_v = \frac{V_o}{V_{sig}} = 15 \text{ V/V}$$

$$R_{in} = \frac{r_o + R_L}{A_{v0}} = \frac{20 + 20}{121} = 0.33 \text{ k}\Omega$$

$$R_{gs} = R_S \parallel R_{in} = 1 \text{ k} \parallel 0.33 \text{ k} = 0.25 \text{ k}\Omega = 250 \Omega$$

$$R_{gd} = R_L \parallel R_{out} = 20 \text{ k} \parallel 141 \text{ k} = 17.5 \text{ k}\Omega$$

$$\tau_H = C_{gs} R_{gs} + (C_L + C_{gd}) R_{gd} = 2 \text{ pF} \times 0.25 \text{ k} + (2 + 0.1) \text{ pF} \times 17.5 \text{ k} = 37.2 \text{ ns}$$

$$f_H = \frac{1}{2\pi \tau_H} = 4.27 \text{ MHz}$$

Comparing with results in Problem 6.86, we notice that gain is reduced by 12.5%, while f_H is increased by 12.7%, when r_o is taken into account.

6.88

$$i_o = i_c - v_i/r_{\pi} \quad \text{Eq. 6.110}$$

If we write a KCL at the emitter node, we

$$\text{will have: } \frac{v_i - i_o R_L}{r_o} + \frac{v_i}{r_e} = i_c$$

Substitute for i_o from Eq. 6.110, then:

$$\frac{v_i - R_L i_c + R_L/r_{\pi} v_i}{r_o} + \frac{v_i}{r_e} = i_c$$

$$v_i \left(\frac{1}{r_o} + \frac{R_L}{r_{\pi} r_o} + \frac{1}{r_e} \right) = i_c \left(1 + \frac{R_L}{r_o} \right)$$

$$R_{in} = \frac{v_i}{i_c} = \frac{1 + R_L/r_o}{\frac{1}{r_o} + \frac{1}{r_e} + \frac{R_L}{r_{\pi} r_o}} = \frac{r_o + R_L}{1 + \frac{r_o}{r_e} + \frac{R_L}{r_{\pi}}}$$

$$r_{\pi} = (\beta + 1) r_e \quad \text{therefore:}$$

$$R_{in} = \frac{r_o + R_L}{1 + \frac{r_o}{r_e} + \frac{R_L}{(\beta + 1) r_e}}$$

This is the same as equation 6.111.

6.89

$$\beta = 100, \quad R_{in} \approx r_e \frac{r_o + R_L}{r_o + R_L/(\beta + 1)}$$

$$R_{in} \approx r_e \frac{1 + R_L/r_o}{1 + \frac{R_L}{r_o} \frac{1}{\beta + 1}}$$

R_L/r_o	0	1	10	100	1000
R_{in}/r_e	1	1.98	10	50.75	91.83

6.90

$$I = 1 \text{ mA}, \quad \text{Intrinsic gain} = A_o = \frac{V_A}{V_T} = 2000 V/V$$

$$V_A = 2000 V_T = 50 \text{ V}$$

$$r_o = \frac{V_A}{I_C} = \frac{50}{1} = 50 \text{ k}\Omega$$

$$\text{From Eq. 6.112 we have: } R_{in} \approx r_e \frac{r_o + R_L}{r_o + R_L/(\beta + 1)}$$

Assuming β is very large so that:

$$\frac{R_L}{\beta + 1} \ll r_o, \quad \text{we have: } R_{in} \approx r_e \frac{r_o + R_L}{r_o}$$

For R_{in} to be $2r_e$, we need:

$$2r_e = r_e \frac{r_o + R_L}{r_o} \Rightarrow r_o = R_L \Rightarrow R_L = 50 \text{ k}\Omega$$

6.91

Refer to Fig. 6.34.

Write KCL at the emitter:

$$\frac{v}{r_e} + \frac{v}{R_E} = i_x + g_m v \Rightarrow v = \frac{i_x}{\frac{1}{r_e} + g_m + \frac{1}{R_E}}$$

$$\text{Note that } \frac{1}{r_e} + g_m = \frac{\beta + 1}{r_{\pi}} + g_m = \frac{\beta + 1 - \beta}{r_{\pi}} = \frac{1}{r_{\pi}}$$

$$\text{therefore: } v = \frac{i_x}{\frac{1}{r_{\pi}} + \frac{1}{R_E}} = (r_{\pi} \parallel R_E) i_x$$

$$v = R'_E i_x \quad \text{where } R'_E = r_{\pi} \parallel R_E$$

Now we write the equation for v :

$$v = v_x - (i_x + g_m v) r_o$$

If we substitute v from ①:

$$R'_E i_x = v_x - i_x r_o - g_m R'_E i_x r_o$$

$$i_x (R'_E + r_o + g_m R'_E r_o) = v_x$$

$$R_{in} = \frac{v_x}{i_x} = r_o + (1 + g_m r_o) R'_E \quad \text{where } R'_E = R_E \parallel r_{\pi}$$

(same as Eq. 6.117)

6.92

$$\text{Eq. 6.118: } R_{out} \approx (1 + g_m R'_E) r_o$$

$$\Rightarrow \frac{R_{out}}{r_o} \approx 1 + g_m R'_E \quad \text{where } R'_E = R_E \parallel r_{\pi}$$

$$R'_E = \frac{r_{\pi} R_E}{r_{\pi} + R_E} = \frac{(\beta + 1) r_e R_E}{(\beta + 1) r_e + R_E} = \frac{(\beta + 1) r_e}{\frac{(\beta + 1) r_e}{R_E} + 1}$$

$$m = \frac{R_E}{r_e} \Rightarrow R'_E = \frac{(\beta + 1) r_e}{\frac{\beta + 1}{m} + 1}$$

$$\frac{R_{out}}{r_o} = 1 + g_m r_e \frac{(\beta + 1)}{\frac{\beta + 1}{m} + 1} = 1 + \frac{g_m r_{\pi} (\beta + 1)}{\frac{\beta + 1}{m} + 1}$$

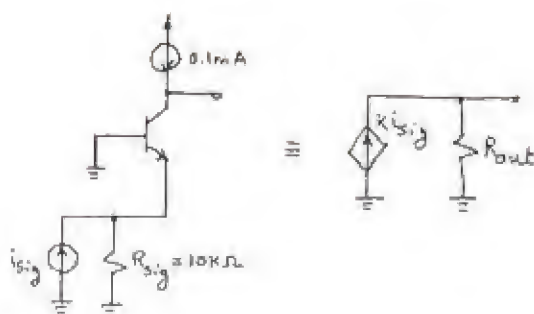
$$\frac{R_{out}}{r_o} = 1 + \frac{\beta}{\frac{\beta + 1}{m} + 1} = \frac{(\beta + 1)(m + 1)}{\beta + 1 + m} = \frac{101(m + 1)}{101 + m}$$

$m = \frac{R_E}{r_e}$	1	2	10	$\beta/2$	1000
$\frac{R_{out}}{r_o}$	1.98	2.94	10.01	$\beta/3 + 1$	91.74

6.93

$$R_{sig} = 10 \text{ k}\Omega, \quad \beta = 100, \quad V_A = 50 \text{ V}, \quad I_C = 0.1 \text{ mA}$$

Cont.

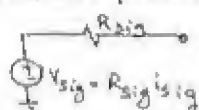


$$r_o = \frac{V_A}{I_C} = \frac{50}{0.1mA} = 500k\Omega$$

$$g_m = \frac{I_C}{V_T} = \frac{0.1}{0.025} = 4mA/V$$

$$r_{\pi} = \frac{\beta}{g_m} = \frac{100}{4} = 25k\Omega$$

The Thevenin equivalent circuit of the source is:



Thus using equations 6.121 and 6.114 we can write:

$$\frac{V_{out}}{V_{sig}} = \frac{r_{\pi}}{r_{\pi} + R_{sig}} A_{v_o} = \frac{r_{\pi}}{r_{\pi} + R_{sig}} (1 + g_m r_o)$$

$$\frac{V_{out}}{i_{sig}} = \frac{r_{\pi} R_{sig}}{r_{\pi} + R_{sig}} (1 + g_m r_o) = (r_{\pi} || R_{sig}) (1 + g_m r_o)$$

$$\frac{V_{out}}{i_{sig}} = 14.29 \times 10^6 V/A$$

From Eq. 6.117a we have $R_{out} = r_o + (1 + g_m r_o) R'_E$ where $R'_E = r_{\pi} || R_{sig}$.

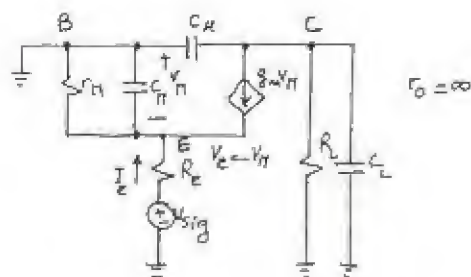
$$R_{out} = 500k + (1 + 4 \times 500k) (25k || 10k) = 14.29M\Omega$$

$$R_{out} = 14.29M\Omega$$

$$V_{out} = K i_{sig} R_{out} \Rightarrow K = \frac{V_{out}}{i_{sig}} \times \frac{1}{R_{out}} = \frac{14.29 \times 10^6}{14.29 \times 10^6}$$

$$\Rightarrow K = 0.97$$

6.94

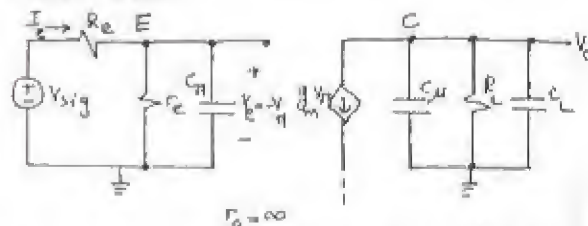


we observe that V_e , the voltage at the emitter is equal to $-V_{\pi}$. We can write a node equation at the emitter:

$$I_e = -V_{\pi} \left(\frac{1}{r_{\pi}} + sC_{\pi} \right) - g_m V_{\pi} = V_e \left(\frac{1}{r_{\pi}} + g_m + sC_{\pi} \right)$$

Thus, the input admittance looking into the emitter is: $\frac{I_e}{V_e} = \frac{1}{r_{\pi}} + g_m + sC_{\pi} = \frac{1}{r_e} + sC_{\pi}$

Therefore we can replace the transistor at the input of the circuit by this admittance as shown below:



a) As we can see above, the circuit can be separated into two parts with each part having its own pole:

$$f_{p1} = \frac{1}{2\pi C_{\pi} (R_{sig} || r_e)} \quad (\text{input part})$$

$$f_{p2} = \frac{1}{2\pi (C_{\mu} + C_L) R_L} \quad (\text{output part})$$

If we compare the poles to Eq. 6.105 and 6.106 for MOSFETs, we observe that these equations are the bipolar counterparts of those ones.

$$f_{p1} = \frac{1}{2\pi C_{\pi} (R_{sig} || \frac{1}{g_m + g_{mb}})} \quad (6.105)$$

$$f_{p2} = \frac{1}{2\pi (C_{\mu} + C_L) R_L} \quad (6.106)$$

b) For $C_{\pi} = 14pF$, $C_{\mu} = 2pF$, $C_L = 1pF$, $I_C = 1mA$, $R_{sig} = 1k\Omega$, $R_L = 10k\Omega$. $\Rightarrow g_m = \frac{1}{0.025} = 40mA/V$

$$f_{p1} = \frac{1}{2\pi \times 14pF (1k || \frac{100}{40})} \quad (\text{Assuming } \beta = 100)$$

$$f_{p1} = 15.9MHz$$

$$f_{p2} = \frac{1}{2\pi (2+1)pF \times 10k} = 5.3MHz$$

$$f_T = \frac{g_m}{2\pi (C_{\pi} + C_{\mu})} = \frac{40m}{2\pi (14+2)pF} = 398.1MHz$$

f_T is much greater than the poles. $f_T \gg f_{p1}$
 $f_T \gg f_{p2}$

6.95

In Fig. 6.32, if we replace the NMOS with an npn transistor, then we can write:

$$R_{be} = R_e \parallel R_{in} \quad \text{where } R_{in} = r_e \frac{r_o + R_L}{1 + \frac{r_o + R_L}{r_e} + \beta + 1}$$

$$R_{bc} = R_L \parallel R_{out} \quad \text{where } R_{out} = (1 + g_m R_e') r_o$$

using the open-circuit time constants method to evaluate f_H :

$$f_H = \frac{1}{2\pi (C_{\pi} (R_e \parallel R_{in}) + C_L + C_{\mu}) (R_L \parallel R_{out})}$$

6.96

$$\beta = 100, V_A = 100V$$

$$I_C = I_E = \frac{5 - V_{BE}}{4.3k} = \frac{5 - 0.7}{4.3k} = 1mA$$

$$I = 1mA$$



From Eq. 6.117a we have:

$$R_{out} = r_o + (1 + g_m r_o) (r_{\pi} \parallel R_e)$$

$$r_o = \frac{V_A}{I_C} = \frac{100}{1} = 100k\Omega$$

$$g_m = \frac{I_C}{V_T} = \frac{1}{0.025} = 40mA/V$$

$$r_{\pi} = \frac{\beta}{g_m} = 2.5k\Omega, R_e = 4.3k\Omega$$

$$\text{Thus: } R_{out} = 100 + (1 + 40 \times 100) (2.5k \parallel 4.3k)$$

$$R_{out} = 6.43M\Omega$$

If the collector voltage undergoes a change of 10V while the BJT remains in the active mode, the corresponding change in the collector current is:

$$\Delta I = \frac{\Delta V}{R_{out}} = \frac{10}{6.43M} = 1.56\mu A$$

$$\Delta I = 1.56\mu A$$

6.97

$$a) I = \frac{1}{2} K_n' \frac{W}{L} V_{ov}^2 = \frac{1}{2} \times 160\mu \times 100 \times 0.2^2 = 320\mu A$$

$$b) g_m = \frac{2I_D}{V_{ov}} = \frac{2 \times 0.32}{0.2} = 3.2mA/V = g_{m1} = g_{m2}$$

$$g_{mb} = \chi g_m = 0.2 \times 3.2 = 0.64mA/V = g_{mb1} = g_{mb2}$$

$$r_o = \frac{V_A}{I_D} = \frac{1}{\lambda I_D} = \frac{1}{0.05 \times 0.32} = 625k\Omega = r_{o1} = r_{o2}$$

$$A_o = g_m r_o = 3.2 \times 62.5k = 200V/V$$

$$A_{v_{o2}} = 1 + (g_{m2} + g_{mb2}) r_{o2} \quad (\text{Eq. 6.123})$$

$$A_{v_{o2}} = 1 + (3.2 + 0.64) \times 62.5 = 241 \quad V/V$$

$$c) A_{v_o} = -A_{o1} A_{v_{o2}} \quad (\text{Eq. 6.128})$$

$$A_{v_o} = -g_{m1} r_{o1} A_{v_{o2}} = -3.2 \times 62.5 \times 241 = -48200V/V$$

$$A_{v_o} = 48200 \quad V/V$$

$$d) G_m = \frac{A_{o1} A_{v_{o2}}}{r_{o2} + A_{v_{o2}} r_{o1}} \quad (\text{Eq. 6.130})$$

$$G_m = \frac{200 \times 241}{62.5 + 241 \times 62.5} = 3.19mA/V \approx g_m$$

$$R_{out} = r_{o2} + [1 + (g_{m2} + g_{mb2}) r_{o2}] r_{o1} \quad (\text{Eq. 6.126})$$

$$R_{out} = 62.5 + [1 + (3.2 + 0.64) \times 62.5] \times 62.5$$

$$R_{out} = 15.125M\Omega$$

$$e) A_v = -A_o^2 \frac{R_L}{R_L + A_o r_o} \quad (\text{Eq. 6.131})$$

$$A_v = -(200)^2 \frac{10M}{10M + 200 \times 62.5k} = 17778 \quad V/V$$

f) $V_{DS} \gg V_{ov}$ for Q_1 . Therefore $V_{DSmin} = V_{ov}$

$$V_{DSmin} = 0.2V$$

$$V_{BIAS} = V_{GS2} + V_{DSmin} = (0.2 + 0.6) + 0.2 = 1V$$

$$V_{BIAS} = 1V$$

6.98

$$V_y = I_x \times r_{o1} = \frac{V_x}{R_{out}} \times r_{o1} \Rightarrow \frac{V_y}{V_x} = \frac{r_{o1}}{R_{out}}$$

$$\frac{V_y}{V_x} = \frac{r_{o1}}{r_{o2} + [1 + (g_{m2} + g_{mb2}) r_{o2}] r_{o1}}$$

If we use equation 6.127 to approximate

$$R_{out}, \text{ then } \frac{V_y}{V_x} \approx \frac{r_{o1}}{g_{m2} r_{o2} r_{o1}} = \frac{1}{g_{m2} r_{o2}}$$

6.99

a) $I = \frac{1}{2} K_n' \frac{W}{L} V_{ov}^2 \Rightarrow \text{For same } I: \frac{V_{ovb}^2}{V_{ova}^2} = \left(\frac{W}{L} \right)_a \left(\frac{L}{W} \right)_b$
 For same I , if $\frac{W}{L}$ is divided by 4,
 then V_{ov}^2 is multiplied by 4, or equivalently
 Conf.

V_{ov} is doubled.

$g_m = A_n C_{ox} \frac{W}{L} V_{ov}$. Thus g_m for circuit (b) is half of the one for circuit (a).

$A_o = g_m r_o = \frac{2I_D}{V_{ov}} \times \frac{VA}{I_D} = \frac{2VA}{V_{ov}}$. Thus if L is multiplied by 4 and V_{ov} is halved, then A_o is doubled for circuit (b).

In summary, for circuit (b), V_{ov} is doubled, g_m is halved, A_o is doubled.

b) Each transistor in circuit (c) has the same overdrive voltage as the one in circuit (a).

Referring to Eq. 6.129 and 6.130:

$$A_{vo} = -A_o = -(g_m r_o)^2$$

$$G_m \approx g_{m1} = g_{m2} \text{ (same as circuit (a))}$$

Note that for the transistors in circuit (c) the g_m and r_o are the same as the ones in circuit (a). Thus the intrinsic gain for circuit (c), $A_{vo} = -A_o$ where A_o is the intrinsic gain for circuit (a).

In general, circuit (c) has a higher output resistance and for the same V_{ov} of transistors it has lower output swing. The output swing is limited to $2V_{ov}$ on the low side for circuits (b) and (c) while it is only limited to V_{ov} for circuit (a).

6.100

$$a) A_M = -g_m R'_L = -5 \times (20^k \parallel 20^k) = -50 \frac{V}{V}$$

$$R_{gs} = R_{sig} = 20^k \Omega$$

$$R_{gd} = R_{sig} (1 + g_m R'_L) + R'_L = 20^k (1 + 5 \times 20^k \parallel 20^k) + 20^k \parallel 20^k$$

$$R_{gd} = 1030^k \Omega = 1.03^M \Omega$$

We use Eq. 6.57:

$$\tau_H = C_{gs} R_{gs} + C_{gd} R_{gd} + C_L R'_L$$

$$\tau_H = 2^p \times 20^k + 0.2^p \times 1030^k + 1^p \times (20^k \parallel 20^k) = 256 \text{ ns}$$

$$f_H = \frac{1}{2\pi \tau_H} = 622 \text{ kHz}$$

$$|A_M| \cdot f_H = 31.1 \text{ MHz}$$

b) For the cascode amplifier:

$$A_{o1} = g_{m1} r_{o1} = 5 \times 20 = 100 \frac{V}{V}$$

$$A_{vo2} = 1 + (g_{m2} + g_{mb2}) r_{o2} = 1 + (5 + 0.2 \times 5) \times 20^k$$

$$A_{vo2} = 121 \frac{V}{V}$$

$$R_{out} = r_{o2} + A_{vo2} r_{o1} = 20^k + (121 \times 20^k) = 2.44^M \Omega$$

$$A_v = A_{vo} \frac{R_L}{R_L + R_{out}} = -121 \times 100 \times \frac{20}{20 + 2440} = -98.4 \frac{V}{V}$$

Using Eq. 6.137,

$$\tau_H = R_{sig} [C_{gs1} + C_{gd1} (1 + g_{m1} R_{d1})] + R_{d1} (C_{gd1} + C_{db1} + C_{gs2}) + (R_L \parallel R_{out}) (C_L + C_{gd2})$$

$$R_{d1} = r_{o1} \parallel \left\{ \frac{1}{g_{m2} + g_{mb2}} + \frac{R_L}{A_{vo2}} \right\} \quad (\text{Eq. 6.124})$$

$$R_{d1} = 20^k \parallel \left\{ \frac{1}{5 + 0.2 \times 5} + \frac{20}{121} \right\} = 0.327^k \Omega$$

$$\tau_H = 20^k [2 + 0.2 (1 + 5 \times 0.327^k)] + 0.327^k (0.2 + 0.2 + 2) + (20^k \parallel 2.44^M) (1 + 0.2)$$

$$\tau_H = 75.1 \text{ ns}$$

$$f_H = \frac{1}{2\pi \tau_H} = 2.12 \text{ MHz}$$

$$|A_v| \cdot f_H = 208.61 \text{ MHz}$$

6.101

$$A_v = 66 \text{ dB} = 1995 \frac{V}{V}$$

$$A_v = A_{vo} \frac{R_L}{R_L + R_{out}} \text{ and } R_L = R_{out} \Rightarrow A_v = A_{vo} \times \frac{1}{2}$$

$$A_{vo} = (1 + g_{m2} r_{o2}) g_{m1} r_{o1} \approx g_{m1}^2 r_o^2 = \left(\frac{2I_D}{V_{ov}} \right)^2 \left(\frac{VA}{I_D} \right)^2 = \left(\frac{2VA}{V_{ov}} \right)^2$$

$$\Rightarrow 1995 = \frac{1}{2} \times \left(\frac{2 \times 10}{V_{ov}} \right)^2 \Rightarrow V_{ov} = 0.317 \text{ V}$$

$$\Rightarrow I_D = \frac{1}{2} \mu_n \frac{W}{L} V_{ov}^2 \approx \frac{1}{2} \times 200 \times 10^3 \times 10 \times 0.317^2 = 0.1 \text{ mA}$$

Since R_{sig} is small:

$$\tau_H \approx (C_L + C_{gd}) (R_L \parallel R_{out})$$

$$r_o = \frac{VA}{I_D} = \frac{10}{0.1} = 100^k \Omega, g_{m1} = \frac{2I_D}{V_{ov}} = 0.631 \text{ mA/V}$$

$$R_{out} = A_{vo2} r_{o1} + r_{o2} = (1 + g_{m2} r_o) r_o + r_o$$

$$R_{out} = 6510^k \Omega \approx 6.5^M \Omega, R_L = R_{out}$$

$$\tau_H \approx (1 \text{ pF} + 0.1 \text{ pF}) \left(\frac{6510^k}{2} \right) = 3580.5 \text{ ns}$$

$$f_H = 44.5 \text{ kHz}$$

$$f_T \approx |A_v| \cdot f_H = 1995 \times 44.5 = 88.8 \text{ MHz}$$

If the cascode transistor is removed, then we have a common-source configuration.

Cont.

$$A_H = -g_m (r_o \parallel R_L) = -0.637 (100 \text{ k} \parallel 165 \text{ k})$$

$$A_H = -62.74 \text{ V/V}$$

$$f_H = \frac{1}{2\pi(C_L + C_{gd})R_L} = \frac{1}{2\pi(1+0.1)(100 \text{ k} \parallel 165 \text{ k})} = 1.47 \text{ kHz}$$

$$f_H = 1.47 \text{ MHz}$$

$$|A_H| f_H = 92.2 \text{ MHz} \approx f_T$$

Note that the unity-gain stays nearly unchanged. The result is the same as Fig. 6.39.

6.102

$$R_L = \beta r_o, \beta = 100, |V_A| = 100 \text{ V}, I = 0.1 \text{ mA}$$

From Fig. 6.40, we can write:

$$R_{in} = r_{\pi 1} = \frac{\beta}{g_{m1}} = \frac{\beta V_T}{I_C} = \frac{100 \times 0.025}{0.1} = 25 \text{ k}\Omega$$

$$R_{in} = 25 \text{ k}\Omega$$

$$R_{out} \approx \beta r_{o2}, r_{o2} = \frac{V_A}{I_C} = \frac{100}{0.1} = 1 \text{ M}\Omega$$

$$R_{out} = 100 \times 1 \text{ M} = 100 \text{ M}\Omega$$

$$A_{v_o} = -\beta A_{v_{s2}} = -\beta g_{m2} r_{o2} = -100 \times \frac{0.1 \text{ m}}{0.025} \times 1 \text{ M} \Rightarrow$$

$$A_{v_o} = -400 \times 10^3 \text{ V/V}$$

$$G_m = \frac{A_{v_o}}{R_{out}} = \frac{400 \times 10^3}{100 \times 10^6} = 4 \text{ mA/V} \approx g_m$$

$$G_m = 4 \text{ mA/V}$$

Since $R_{out} = R_L = \beta r_o$ we have

$$\frac{v_o}{v_i} = -G_m (R_L \parallel R_{out}) = -G_m \frac{\beta r_o}{2} = -4 \frac{100 \times 1 \text{ M}}{2}$$

$$\frac{v_o}{v_i} = -200 \times 10^3 \text{ V/V}$$

From Fig. 6.41 the gain of the CE stage is

$$A_{CE} = -g_{m1} (r_{o1} \parallel r_{e2} \frac{r_{o2} + R_L}{r_{o2} + \frac{R_L}{\beta+1}})$$

$$r_{o1} = r_{o2} = r_o, R_L = \beta r_o$$

$$A_{CE} = -g_{m1} (r_o \parallel r_{e2} \frac{r_o + \beta r_o}{r_o + \frac{\beta r_o}{\beta+1}})$$

$$A_{CE} = -g_{m1} (r_o \parallel r_{e2} \frac{1 + \beta}{2})$$

$$A_{CE} = -g_{m1} (r_o \parallel \frac{r_{\pi 1}}{2}) = -\frac{I}{V_T} (1 \text{ M} \parallel \frac{25 \text{ k}}{2})$$

$$A_{CE} = -50 \text{ V/V}$$

6.103

$$R_{sig} = 4 \text{ k}\Omega, R_L = 2.4 \text{ k}\Omega, I = 1 \text{ mA}, \beta = 100, r_o = 100 \text{ k}\Omega$$

Refer to Fig. 6.42:

$$A_M = -\frac{r_{\pi}}{r_{\pi} + r_x + R_{sig}} \times g_m (\beta r_o \parallel R_L)$$

$$r_{\pi} = \frac{\beta}{g_m} = \frac{100}{1/0.025} = 2.5 \text{ k}\Omega, g_m = \frac{I_C}{V_T} = 40 \text{ mA/V}$$

$$A_M = -\frac{2.5}{2.5 + 0.05 + 4} \times 40 \times (100 \times 100 \parallel 2.4 \text{ k})$$

$$A_M = -36.6 \text{ V/V}$$

$$R'_{sig} = r_{\pi} \parallel (r_x + R_{sig}) = 2.5 \text{ k} \parallel (0.05 + 4 \text{ k})$$

$$R'_{sig} = 1.55 \text{ k}\Omega$$

$$R_{\pi 1} = R'_{sig} = 1.55 \text{ k}\Omega$$

$$R_{\mu 1} = R'_{sig} (1 + g_m R_{e1}) + R_{e1}$$

$$R_{e1} = r_{o1} \parallel r_{e2} \left(\frac{r_o + R_L}{r_o + R_L / \beta + 1} \right) = 100 \text{ k} \parallel \frac{100 \text{ k}}{101} \left(\frac{100 + 2.4}{100 + \frac{2.4}{101}} \right)$$

$$R_{e1} = 1 \text{ k}\Omega$$

$$R_{\mu 1} = 1.55 (1 + 40 \times 1) + 1 = 64.55 \text{ k}\Omega$$

$$R_{out} = \beta r_o = 10 \text{ M}\Omega$$

$$\tau_H = C_{\pi 1} R_{\pi 1} + C_{\mu 1} R_{\mu 1} + (C_{\pi 1} + C_{\pi 2}) R_{e1} + (C_L + C_{\pi 2} + C_{\mu 2}) (R_L \parallel R_{out})$$

$$\tau_H = 14 \times 1.55 + 2 \times 64.55 + (10 + 14) \times 1 + (0 + 2) (2.4 \text{ k} \parallel 10 \text{ M})$$

$$\tau_H = 169.6 \text{ ns}$$

$$f_H = 939 \text{ kHz}$$

6.104

a) If we employ Miller's theorem to $C_{\mu 1}$:

$$\frac{1}{C_{\mu 1} S} \frac{1}{1-A} = \frac{1}{C_{\mu 1} S} \frac{1}{1-(-1)} = \frac{1}{2C_{\mu 1} S}$$

or $2C_{\mu 1}$ appears in parallel with $C_{\pi 1}$. Thus the time constant due to $(C_{\pi 1} + 2C_{\mu 1})$ is:

$R'_{sig}(C_{\pi 1} + 2C_{\mu 1})$ which results in:

$$f_{p1} = \frac{1}{2\pi R'_{sig}(C_{\pi 1} + 2C_{\mu 1})}$$

If we refer to Fig. 6.42, we'll see that the

output pole is: $f_{p2} = \frac{1}{2\pi(C_L + C_{\pi 2} + C_{\mu 2})R_L}$

$$b) R_{sig} = 1 \text{ k}\Omega \Rightarrow R'_{sig} = r_{\pi} \parallel R_{sig} = \frac{100}{1/0.025} \parallel 1 \text{ k} \Rightarrow R'_{sig} = 0.714 \text{ k}\Omega$$

$$f_{p1} = \frac{1}{2\pi \times 0.714 \times (5 + 2 \times 1) \text{ p}} = 31.85 \text{ MHz}$$

$$f_{p2} = \frac{1}{2\pi(0 + 0 + 1) \times 10} = 15.9 \text{ MHz}$$

$$(\text{Assume } R_L = 10 \text{ k}\Omega)$$

Cont.

$$f_H = \frac{1}{\sqrt{\left(\frac{1}{f_{p1}}\right)^2 + \left(\frac{1}{f_{p2}}\right)^2}} = 14.2 \text{ MHz}$$

IF $R_{sig} = 10 \text{ k}\Omega$:

$$R'_{sig} = 2.5 \times 110 \text{ k}\Omega = 2 \text{ k}\Omega$$

$$f_{p1} = \frac{1}{2\pi(5+2)\tau} = 11.4 \text{ MHz}$$

f_{p2} is the same: $f_{p2} = 11.4 \text{ MHz}$

$$f_H = 9.26 \text{ MHz}$$

6.105

Refer to Fig. 6.43.

$$I = \frac{1}{2} \mu_p C_{ox} \frac{W}{L} V_{ov}^2 \Rightarrow 100 \mu\text{A} = \frac{1}{2} \times 60 \frac{\text{W}}{\text{L}} \times 0.2^2$$

$$\Rightarrow \frac{W}{L} = 83.3$$

$$V_{SG1} = V_{DD} - V_{BIAS1} = 3.3 - V_{BIAS1}$$

$$V_{ov} = V_{SG1} - |V_{tp}| = 0.2 \Rightarrow 0.2 = 3.3 - V_{BIAS1} - 0.8$$

$$\Rightarrow V_{BIAS1} = 2.3 \text{ V}$$

For Maximum Swing: $V_{SD1} = V_{ov} \Rightarrow V_{D1} = 3.3 - 0.2 = 3.1 \text{ V}$

$$\Rightarrow V_{D1} = 3.1 \text{ V}$$

$$\text{then: } V_{SG2} - |V_{tp}| = V_{ov} \Rightarrow 3.1 - V_{BIAS2} - 0.8 = 0.2$$

$$V_{BIAS2} = 2.1 \text{ V}$$

The highest allowable voltage at the output

$$\text{is } V_{DD} - V_{ov} - V_{ov} = 3.3 - 0.2 - 0.2 = 2.9 \text{ V}$$

$$R_o = g_{m2} r_{o2} r_{o1} \quad (\text{Eq. 6.141})$$

$$g_m = \frac{I_c}{V_T} = \frac{0.1}{0.025} = 4 \text{ mA/V} \quad r_o = \frac{V_A}{I_c} = \frac{5}{0.1} = 50 \text{ k}\Omega$$

$$R_o = 4 \times 50 \times 50 = 10 \text{ M}\Omega$$

$$R_o = 10 \text{ M}\Omega$$

6.106

$$I_D = 0.2 \text{ mA} \Rightarrow g_m = \frac{2I_D}{V_{ov}} = \frac{2 \times 0.2}{0.25} = 1.6 \text{ mA/V}$$

$$r_o = \frac{V_A}{I_D} = \frac{5}{0.2} = 25 \text{ k}\Omega$$

$$R_{out} = A_o r_o, \quad A_o = g_m r_o = 1.6 \times 25 = 40 \text{ V/V}$$

$$R_{out} = 40 \times 40 \times 25 = 40 \text{ M}\Omega$$

6.107

$$I = 100 \mu\text{A}, \quad V_{BIAS} = 1 \text{ V}$$

$$a) I_{C1} = 2I - I_{E2} = 2I - I = I = 100 \mu\text{A}$$

$$b) V_X = V_{BIAS} + V_{BE} = 1 + 0.7 = 1.7 \text{ V}$$

$$c) g_{m1} = \frac{I_{C1}}{V_T} = \frac{0.1}{0.025} = 4 \text{ mA/V} = g_{m2}$$

$$r_{o1} = r_{o2} = \frac{V_A}{I_C} = \frac{100}{0.1} = 1 \text{ M}\Omega$$

$$d) V_{omax} = V_X - V_{CESat}$$

$$V_{omax} = 1.7 - 0.2 = 1.5 \text{ V}$$

$$e) R_i = r_{\pi1} = \frac{\beta}{g_{m1}} = \frac{100}{4} = 25 \text{ k}\Omega$$

f) Since the output resistance

of the current source is equal to R_o , then the

overall output resistance $R_{out} = \frac{R_o}{2}$.

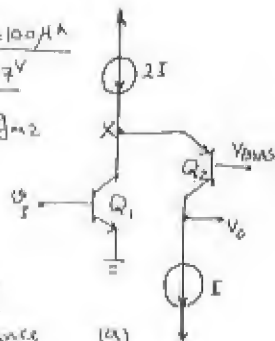
$$R_o = \beta r_o = 100 \times 1 \text{ M} = 100 \text{ M}\Omega \Rightarrow R_{out} = 50 \text{ M}\Omega$$

g) $A_M \approx g_m (\beta r_o \parallel R_L)$ where $R_L = \beta r_o$

$$A_M = g_m \frac{\beta r_o}{2} = 4 \times 100 \times \frac{1 \text{ M}}{2} = 200 \times 10^6 \text{ V/V}$$

The current source $2I$ should

ideally have infinite output resistance.



$$a) I_1 = 2I - I = I = 100 \mu\text{A}$$

$$b) V_X = V_{BIAS} + V_{SG}$$

$$I = \frac{1}{2} \mu_p C_{ox} \frac{W}{L} V_{ov}^2$$

$$0.1 = \frac{1}{2} \times 2 \times V_{ov}^2 \Rightarrow V_{ov} = 0.316 \text{ V}$$

$$V_{SG} = |V_{tp}| + V_{ov} = 0.6 + 0.316$$

$$V_{SG} = 0.916 \text{ V} \Rightarrow V_X = 1 \text{ V} + 0.916 \text{ V} = 1.916 \text{ V}$$

$$c) g_{m1} = \frac{0.1}{0.025} = 4 \text{ mA/V}$$

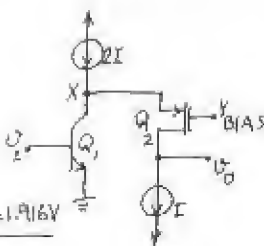
$$g_{m2} = \frac{2I_D}{V_{ov}} = \frac{2 \times 0.1}{0.316} = 0.633 \text{ mA/V}$$

$$r_{o1} = \frac{100}{0.1} = 1 \text{ M}\Omega, \quad r_{o2} = \frac{5}{0.1} = 50 \text{ k}\Omega$$

$$d) V_{omax} = V_X - V_{SDmin} = V_X - V_{ov} = 1.916 - 0.316 = 1.6 \text{ V}$$

$$e) R_i = r_{\pi1} = \frac{\beta}{g_{m1}} = \frac{100}{4} = 25 \text{ k}\Omega$$

$$f) R_{out} = R_{out1} \parallel [1 + (g_{m1} + g_{m2}) R_{out1}] r_{o2}$$



Cont.

$$R_{out1} = r_{o1}$$

$$R_{out} = r_{o2} + [1 + g_{m2} r_{o2}] r_{o1} = 50k + 0.633 \times 10^4 \times 50k$$

$$R_{out} = 31.7 M\Omega$$

f) First note that R_{L2} or the output resistance of the current source is equal to $R_{out} = 31.7 M\Omega$

$$R_{L2} = 32.6 M\Omega \quad \text{or} \quad R_{L2} \approx g_{m2} r_{o1} r_{o2}$$

$$\frac{v_x}{v_i} = -g_{m1} (r_{o1} \parallel R_{in2})$$

$$R_{in2} = \frac{1}{g_{m2}} + \frac{R_{L2}}{A_{o2}} = \frac{1}{g_{m2}} + \frac{g_{m2} r_{o1} r_{o2}}{g_{m2} r_{o2}} = \frac{1}{g_{m2}} + r_{o1}$$

$$\frac{v_x}{v_i} = -g_{m1} (r_{o1} \parallel (r_{o1} + \frac{1}{g_{m2}})) \approx -g_{m1} \times \frac{r_{o1}}{2} = -2000 \frac{V}{V}$$

$$\frac{v_o}{v_x} = (1 + g_{m2} r_{o2}) \frac{R_{L2}}{R_{L2} + R_{out}} = (1 + 0.633 \times 50) \times \frac{1}{2} = 16.3 \frac{V}{V}$$

$$\frac{v_o}{v_i} = -2000 \times 16.3 = -32600 \frac{V}{V}$$

In order for the output resistance of the current-source to reduce the gain by $\frac{1}{10}$:

$$\frac{v_x}{v_i} = -g_{m1} (r_{o1} \parallel (r_{o1} + \frac{1}{g_{m2}}) \parallel R) \approx -g_{m1} (\frac{r_{o1}}{2} \parallel R)$$

For $\frac{v_x}{v_i} = -\frac{99}{100} \times 2000 = 1980$ we should have:

$$\frac{r_{o1} \parallel R}{2} = \frac{1980}{4} = 495k \Rightarrow 500k \parallel R = 495k \Rightarrow$$

$$R = 49.5 M\Omega \quad (\text{This is the output resistance of the } 2I \text{ current-source})$$

(Note that $\frac{v_o}{v_x}$ did not depend on R)

$$a) I_1 = 2I - I = 100 \mu A$$

$$b) V_X = V_{B1AS} + V_{S6}$$

$$I = \frac{1}{2} \mu \frac{W}{L} \frac{V_{OV}^2}{V_{OV}} \Rightarrow V_{OV} = 0.316V$$

$$V_{S6} = 0.6 + 0.316 = 0.916V$$

$$V_X = 1 + 0.916 = 1.916V$$

$$c) g_{m1} = g_{m2} = \frac{2I_D}{V_{OV}} = \frac{0.1 \times 2}{0.316} = 0.633 \text{ mA/V}$$

$$r_{o1} = r_{o2} = \frac{50}{0.1} = 500k\Omega$$

$$d) V_{Omax} = V_X - V_{DSMin} = V_X - V_{OV} = 1.916 - 0.316 = 1.6V$$

$$e) R_{in} = \infty$$

$$f) R_{out} = r_{o2} + (1 + g_{m2} r_{o2}) r_{o1} = 50 + (1 + 0.633 \times 50) \times 50$$

$$R_{out} = 1682.5k = 1.68 M\Omega = R_{L2} \approx g_{m2} r_{o2} r_{o1}$$

$$g) \frac{v_x}{v_i} = -g_{m1} (r_{o1} \parallel R_{in2})$$

$$R_{in2} = \frac{1}{g_{m2}} + \frac{R_{L2}}{A_{o2}} \approx \frac{1}{g_{m2}} + \frac{g_{m2} r_{o2} r_{o1}}{g_{m2} r_{o2}} = \frac{1}{g_{m2}} + r_{o1}$$

Note that R_{L2} is the output resistance of the current source I :

$$\frac{v_x}{v_i} = -g_{m1} (r_{o1} \parallel (\frac{1}{g_{m2}} + r_{o1})) = -0.633 \times (50k \parallel (\frac{1}{0.633} + 50k))$$

$$\frac{v_x}{v_i} = -16.07 \frac{V}{V}$$

$$\frac{v_o}{v_x} = (1 + g_{m2} r_{o2}) \frac{R_{L2}}{R_{L2} + R_{out}} = (1 + 0.633 \times 50) \times \frac{1}{2}$$

$$\frac{v_o}{v_x} = 16.32 \frac{V}{V}$$

$$\frac{v_o}{v_i} = -262.34 \frac{V}{V}$$

In order to reduce the gain by $\frac{1}{10}$ by introducing non-ideal current-source $2I$ with output resistance R :

$$\frac{v_x}{v_i} = -g_{m1} (r_{o1} \parallel R \parallel (\frac{1}{g_{m2}} + r_{o1})) = \frac{90}{100} \times 16.07 \times 14.46$$

$$\Rightarrow (50k \parallel R \parallel (51.58k)) = \frac{14.46}{0.633} \Rightarrow R = 227.5k$$

$$a) I_1 = 2I - I = I = 0.1 \text{ mA}$$

$$b) V_X = V_{B1AS} + 0.7 = 1.7V$$

$$c) g_{m1} = \frac{2I_D}{V_{OV}}$$

$$V_{OV} = \frac{0.1}{2 \times \frac{1}{2}} \Rightarrow V_{OV} = 0.316V$$

$$g_{m1} = 0.633 \text{ mA/V}$$

$$r_{o1} = \frac{50}{0.1} = 500k\Omega$$

$$g_{m2} = \frac{0.1}{0.025} = 4 \text{ mA/V}, \quad r_{o2} = \frac{V_A}{I_C} = \frac{100}{0.1} = 1M\Omega$$

$$d) V_{Omax} = V_X - V_{DSsat} = V_X - 0.2 = 1.5V$$

$$e) R_{in} = \infty$$

$$f) R_{out} = r_{o2} (1 + g_{m2} (r_{o1} \parallel R))$$

$$R_{out} = 1M (1 + 4 (50k \parallel \frac{100k}{4})) = 67.67 M\Omega$$

$$R_{L2} = R_{out}$$

$$g) \frac{v_x}{v_i} = -g_{m1} (r_{o1} \parallel R_{in2}) = -g_{m1} (r_{o1} \parallel \frac{r_{o2} + R_{L2}}{r_{o2} + R_{L2}/\beta_{A1}})$$

$$r_{L2} = \frac{r_{L2}}{\beta_{A1}} = \frac{A}{\beta_{A1} g_{m2}} = 3.95k\Omega$$

$$\frac{v_x}{v_i} = -4 (50k \parallel \frac{1M + 67.67M}{1 + \frac{67.67}{101}} \times 3.95k) = -152.86 \frac{V}{V}$$

$$\frac{v_o}{v_x} = (1 + g_{m2} r_{o2}) \frac{R_{L2}}{R_{L2} + R_{out}} = (1 + g_{m2} r_{o2}) \times \frac{1}{2}$$

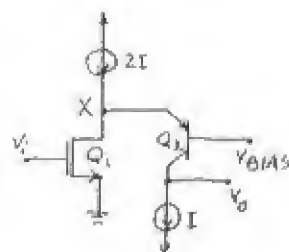
$$\frac{v_o}{v_x} = (1 + 4 \times 1000) \times \frac{1}{2} = 2000.5 \frac{V}{V}$$

$$\frac{v_o}{v_i} = -152.86 \times 2000.5 = -305.8 \times 10^3 \frac{V}{V}$$

To reduce the gain by $\frac{1}{10}$, the effect of R in

$$\frac{v_x}{v_i} \text{ is considered: } 0.99 \frac{v_x}{v_i} = 0.99 \times 152.86$$

(cont.)



$$0.99 \times 152.86 = 4 \times (50^k \parallel \frac{1+67.67}{1+67.67} \parallel 11R)$$

$$\Rightarrow R = 3.74 \text{ k}\Omega$$

6.108

$$g_m = 2 \text{ mA/V} \Rightarrow g_{mb} = \chi g_m = 0.2 \times 2 = 0.4 \text{ mA/V}$$

$$R_{out} = r_o [1 + (g_m + g_{mb}) R_s] = 50^k [1 + (2 + 0.4) \times 0.5^k]$$

$$R_{out} = 110 \text{ k}\Omega$$

$$A_{v0} = -g_m r_o = -2 \times 50 = -100 \text{ V/V}$$

$$A_v = -A_{v0} \frac{R_L}{R_L + R_{out}} = -100 \times \frac{50}{50 + 110} = -31.25 \text{ V/V}$$

using Eq. 6.144:

$$G_m = \frac{g_m}{1 + (g_m + g_{mb}) R_s} = \frac{2}{1 + (2 + 0.2) \times 0.5}$$

$$\Rightarrow G_m = 0.91 \text{ mA/V}$$

$$\frac{V_{gs}}{V_i} = \frac{1}{1 + (g_m + g_{mb}) R_s} \frac{R_L \parallel R_{out}}{R_L \parallel r_o} \quad (\text{Eq. 6.144})$$

$$\frac{V_{gs}}{V_i} = 0.625 \Rightarrow V_{gs} = 0.625 V_i$$

6.109

$$\frac{V_{gs}}{V_i} = \frac{1}{3} \quad \text{using Eq. 6.144:}$$

$$\frac{V_{gs}}{V_i} = \frac{1}{1 + (g_m + g_{mb}) R_s} \frac{R_L \parallel R_{out}}{R_L \parallel r_o}$$

$$\Rightarrow \frac{1}{3} = \frac{1}{1 + (2 + 0.2 \times 2) R_s} \times \frac{50^k \parallel 150^k}{50^k \parallel 150^k} \quad (1)$$

$$R_{out} = r_o [1 + (g_m + g_{mb}) R_s] = 50(1 + 2.4 R_s)$$

$$R_{out} = 50(1 + 2.4 R_s)$$

substitute in (1):

$$\frac{1}{3} = \frac{1}{1 + 2.4 R_s} \frac{50^k \times 50(1 + 2.4 R_s)}{50 + 50(1 + 2.4 R_s)} \times \frac{1}{2.5}$$

$$\Rightarrow R_s = 1.67 \text{ k}\Omega$$

$$\Rightarrow R_{out} = 50(1 + 2.4 \times 1.67) = 250.4 \text{ k}\Omega$$

$$A_v = -A_{v0} \frac{R_L}{R_L + R_{out}} = -g_m r_o \frac{R_L}{R_L + R_{out}}$$

$$A_v = -2 \times 50 \times \frac{50}{50 + 250.4} = -16.64 \text{ V/V}$$

6.110

a) $A_H = -A_{v0} \frac{R_L}{R_L + R_{out}} = -g_m r_o \frac{R_L}{R_L + r_o}$

$$A_H = -5 \times 40 \times \frac{40}{40 + 40} = -100 \text{ V/V}$$

$$R'_L = R_L \parallel R_{out} = R_L \parallel r_o = 20 \text{ k}\Omega$$

$$R_{gd} = R_{sig} (1 + G_m R'_L) \quad \text{where } G_m = g_m \quad (\text{Eq. 6.14})$$

$$\Rightarrow R_{gd} = 20^k (1 + 5 \times 20) = 2020 \text{ k}\Omega = 2.02 \text{ M}\Omega$$

$$R_{gd} = 2.02 \text{ M}\Omega$$

$$R_g = 0 \Rightarrow R_{gs} = R_{sig} = 20 \text{ k}\Omega$$

$$R_{CL} = R'_L = 20 \text{ k}\Omega$$

$$\tau_H = C_{gs} R_{gs} + C_{gd} R_{gd} + C_L R_{CL}$$

$$\tau_H = 2 \times 20^k + 0.1 \times 2.02 \text{ M} + 1 \times 20^k = 262 \text{ ns}$$

$$f_H = \frac{1}{2\pi \tau_H} = \frac{607.8 \text{ kHz}}{2\pi \tau_H}$$

$$|A_H| \cdot f_H = 100 \times 607.8 = 60.78 \times 10^3 \text{ Hz} = 60.78 \text{ MHz}$$

b) $R_s = 500 \Omega$

$$R_{out} = r_o [1 + (g_m + g_{mb}) R_s] = 40 [1 + (5 + 1) \times 0.5] = 160^k$$

$$A_H = -g_m r_o \frac{R_L}{R_L + R_{out}} = -5 \times 40 \times \frac{40}{40 + 160} = -10 \text{ V/V}$$

$$R'_L = R_L \parallel R_{out} = 40^k \parallel 160^k = 32 \text{ k}\Omega$$

$$R_{gd} = R_{sig} (1 + G_m R'_L) \quad (\text{Eq. 6.144})$$

$$G_m = \frac{g_m r_o}{r_o [1 + (g_m + g_{mb}) R_s]} \quad (\text{Eq. 6.144})$$

$$G_m = \frac{5 \times 40}{40 [1 + (5 + 1) \times 0.5]} = 1.25 \text{ mA/V}$$

$$R_{gd} = 20^k (1 + 1.25 \times 32^k) = 820 \text{ k}\Omega$$

$$R_{gs} = \frac{R_{sig} + R_s}{1 + (g_m + g_{mb}) R_s \frac{r_o}{r_o + R_L}} \quad (\text{Eq. 6.151})$$

$$R_{gs} = \frac{20^k + 0.5^k}{1 + (5 + 1) \times 0.5 \times \frac{40}{40 + 40}} = 8.2 \text{ k}\Omega$$

$$R_{CL} = R_L \parallel R_{out} = R'_L = 32 \text{ k}\Omega$$

$$\tau_H = C_{gs} R_{gs} + C_{gd} R_{gd} + C_L R_{CL} = 2 \times 8.2 + 0.1 \times 820 + 32 \times$$

$$\tau_H = 130.4 \text{ ns}$$

$$f_H = \frac{1}{2\pi \tau_H} = 1.22 \text{ MHz}$$

$$|A_H| \cdot f_H = 48.8 \text{ MHz}$$

6.111

Using Eq. 6.151: $R_{gs} = \frac{R_{sig} + R_s}{1 + (g_m + g_{mb}) R_s \frac{r_o}{r_o + R_L}}$

if we define:

$$K = (g_m + g_{mb}) R_s \quad \text{and } R_{sig} \gg R_s$$

then: $R_{gs} = \frac{R_{sig}}{1 + K \frac{r_o}{r_o + R_L}} = \frac{R_{sig}}{1 + K/2}$

Using Eq. 6.144: $G_m = \frac{g_m}{1 + (g_m + g_{mb}) R_s} = g_m / (K + 1)$

Cont.

$$R'_L = R_L \parallel R_{out}$$

$$R_{out} = r_o [1 + (g_m + g_{mb}) R_S] = r_o (1 + K)$$

$$R'_L = r_o \parallel r_o (1 + K) = r_o \frac{1 + K}{2 + K}$$

Using Eq. 6.148:

$$R_{gd} = R_{sig} (1 + G_m R'_L) + R'_L$$

$$R_{gd} = R_{sig} (1 + \frac{g_m}{1 + K} \times r_o \frac{1 + K}{2 + K}) + r_o \frac{1 + K}{2 + K}$$

$$R_{gd} = R_{sig} (1 + \frac{A_v}{2 + K}) + r_o \frac{1 + K}{2 + K}$$

$$R_{L2} = R'_L = r_o \frac{1 + K}{2 + K}$$

$$\tau_H = R_{gs} C_{gs} + R_{gd} C_{gd} + R_{L2} C_{L2}$$

$$\tau_H = \frac{R_{sig}}{1 + K/2} C_{gs} + R_{sig} (1 + \frac{A_v}{2 + K}) C_{gd} + (C_L + C_{gd}) r_o \frac{1 + K}{2 + K}$$

6.112

$$R_{out} = r_o [1 + (g_m + g_{mb}) R_S] = r_o (1 + K)$$

$$R_{out} = 40(1 + K)$$

$$A_M = -g_m r_o \frac{R_L}{R_L + R_{out}} = -5 \times 40 \times \frac{40}{40 + 40(1 + K)}$$

$$A_M = -\frac{200}{2 + K}$$

$$\tau_H = \frac{C_{gs} R_{sig}}{1 + K/2} + C_{gd} R_{sig} (1 + \frac{A_v}{2 + K}) + (C_L + C_{gd}) r_o \frac{1 + K}{2 + K}$$

(From problem 6.111)

$$\tau_H = \frac{25 \times 20 \times 10^{-9}}{1 + K/2} + 0.1 \times 20 \times 10^{-9} (1 + \frac{5 \times 40}{2 + K}) + (1 + 0.1) 40 \times 10^{-9} \frac{1 + K}{2 + K}$$

$$\tau_H = \frac{80}{2 + K} + 2(1 + \frac{200}{2 + K}) + 44 \frac{1 + K}{2 + K}$$

$$\tau_H = \frac{528 + 46K}{2 + K} \text{ ns}$$

$$f_H = \frac{1}{2\pi \tau_H} = \frac{(2 + K) \times 10^3}{2\pi(528 + 46K)} \text{ MHz}$$

$$F_T = |A_M| \cdot f_H$$

K	$A_M (\text{V/V})$	$f_H (\text{MHz})$	$ A_M \cdot f_H (\text{MHz})$
0	-100	0.603	60.3
1	-66.67	0.832	55.47
2	-50.00	1.027	51.35
3	-40.00	1.195	47.8
4	-33.33	1.342	44.73
5	-28.57	1.471	42.03
6	-25.00	1.584	39.6
7	-22.22	1.686	37.46
8	-20.00	1.777	35.54
9	-18.18	1.859	33.8
10	-16.67	1.934	32.24
11	-15.38	2.002	30.79

K	$A_M (\text{V/V})$	$f_H (\text{MHz})$	$ A_M \cdot f_H$
12	-14.28	2.064	29.47
13	-13.33	2.121	28.27
14	-12.5	2.174	26.75
15	-11.76	2.223	26.14

If $f_H = 2 \text{ MHz}$, then by looking at the table,

$K = 11$. Therefore: $K = 11 = (g_m + g_{mb}) R_S \Rightarrow$

$$R_S = \frac{11}{5 + 1} = 1.83 \text{ k}\Omega$$

From the table: $A_M = -15.38$

6.113

a) Eq. 6.156: Gain-Bandwidth product $= |A_M| \cdot f_H$

$$|A_M| \cdot f_H = \frac{1}{2\pi C_{gd} R_{sig}}$$

For $C_{gd} = 0.1 \text{ pF}$, $R_{sig} = 10 \text{ k}\Omega$:

$$|A_M| \cdot f_H = 159.2 \text{ MHz}$$

b) If $|A_M| = 20 \text{ V/V}$, then $f_T = 159.2 \text{ MHz}$,

$$f_H = \frac{159.2}{20} = 7.96 \text{ MHz}$$

c) $g_m = 5 \text{ mA/V}$, $\lambda = 0.2 \Rightarrow g_{mb} = 1 \text{ mA/V}$

$$A_v = 100 \text{ V/V}, R_L = 20 \text{ k}\Omega$$

$$r_o = \frac{A_v}{g_m} = \frac{100}{5} = 20 \text{ k}\Omega = R_L$$

$$A_v = -A_s \frac{R_L}{R_L + R_{out}} \Rightarrow 20 = -100 \frac{20}{R_{out} + 20}$$

$$\Rightarrow R_{out} = 80 \text{ k}\Omega$$

$$R_{out} = r_o [1 + (g_m + g_{mb}) R_S] = 20 [1 + (5 + 1) R_S] = 80$$

$$\Rightarrow 1 + 6 R_S = 4 \Rightarrow R_S = 0.5 \text{ k}\Omega = 500 \Omega$$

$$R_S = 500 \Omega$$

6.114

$R_E = 100 \Omega$, $I = 0.5 \text{ mA}$, $\beta = 100$, $V_A = 100 \text{ V}$, $R_L = r_o$

$$R_{in} = (\beta + 1) r_e + (\beta + 1) R_E \frac{1}{1 + R_E/r_o} \text{ when } \frac{R_L}{\beta + 1} \ll r_o$$

(Eq. 6.158)

$$r_e = \frac{\beta}{g_m} = \frac{100}{0.5/0.025} = 5 \text{ k}\Omega$$

$$g_m = \frac{I}{V_T} = 20 \text{ mA/V}$$

$$r_o = \frac{V_A}{I_C} = \frac{100}{0.5} = 200 \text{ k}\Omega$$

$$r_e = \frac{r_o}{(\beta + 1)} = \frac{200 \text{ k}\Omega}{101} = 1.98 \text{ k}\Omega$$

Cont.

$$R_{in} = (1+100)0.0495 + (1+100) \times 0.1 \frac{1}{1+1}$$

$$R_{in} = 10.05 \text{ k}\Omega$$

$$R_o \approx r_o (1 + g_m R'_c) \quad \text{where } R'_c = R_c \parallel r_{\pi} \text{ (Eq. 6.160)}$$

$$R_o = 200(1 + 20 \times 0.1 \parallel 5 \text{ k}\Omega) = 592.2 \text{ k}\Omega$$

$$R_o = 592.2 \text{ k}\Omega$$

$$A_{v_o} = -g_m R_o = -20 \times 200 = -4000 \text{ V/V}$$

$$G_m = \frac{-A_{v_o}}{R_o} = \frac{6.75 \text{ mA/V}}{R_o}$$

$$A_v = \frac{A_{v_o} R_L}{R_o + R_L} = \frac{-4000 \times 200}{200 + 592.2} = -1009.8 \text{ V/V}$$

$$A_v = -1009.8 \text{ V/V}$$

$$G_v = \frac{V_o}{V_{sig}} = \frac{R_{in}}{R_{in} + R_{sig}} A_v \frac{R_L}{R_L + R_o} = \frac{R_{in}}{R_{in} + R_{sig}} A_v$$

$$G_v = \frac{10.05}{10.05 + 10} \times (-1009.8) = -506.2 \text{ V/V}$$

6.115

$$g_m = \frac{I}{V_T} = 20 \text{ mA/V}$$

Assume $R_{sig} = 10 \text{ k}\Omega$

$$r_{\pi} = \frac{\beta}{g_m} = 5 \text{ k}\Omega$$

$$r_e = \frac{r_{\pi}}{100 + 1} = 49.5 \Omega$$

$$r_o = \frac{V_A}{I_C} = \frac{100}{0.5} = 200 \text{ k}\Omega$$

$$R_{in} = (\beta + 1)r_e + (\beta + 1)R_L \frac{1}{1 + R_L/r_o} \quad \text{(Eq. 6.159)}$$

$$R_{in} = 101 \times 49.5 + 101 \times 100 \times \frac{1}{2} = 10049.5 \approx 10.05 \text{ k}\Omega$$

$$R_{in} = 10.05 \text{ k}\Omega$$

$$R_i = (\beta + 1)(r_e + R_e) = 101 \times (49.5 + 100) = 15.1 \text{ k}\Omega$$

$$R_i = 15.1 \text{ k}\Omega$$

$$A_{v_o} = -g_m R_o = -20 \times 200 = -4000 \text{ V/V}$$

$$G_{v_o} = \frac{R_i}{R_i + R_{sig}} A_{v_o} = \frac{15.1}{15.1 + 10} \times 4000 = -2406.4 \text{ V/V}$$

$$R_o = r_o (1 + g_m R'_c)$$

$$R'_c = R_c \parallel r_{\pi} = 0.1 \text{ k}\Omega \parallel 5 \text{ k}\Omega = 0.1 \text{ k}\Omega$$

$$R_o = 200(1 + 20 \times 0.1) = 600 \text{ k}\Omega$$

$$G_v = \frac{R_{in}}{R_{in} + R_{sig}} A_v = \frac{10.05}{10.05 + 10} \times 4000 \times \frac{200}{200 + 600}$$

$$\text{(Note that } A_v = A_{v_o} \frac{R_L}{R_L + R_o} \text{)}$$

$$G_v = 501.25 \text{ V/V}$$

$$G_v = G_{v_o} \frac{R_L}{R_L + R_{out}} \Rightarrow 501.25 = 2406.4 \frac{200}{200 + R_{out}}$$

$$R_{out} = 760.16 \text{ k}\Omega$$

6.116

a) Eq. 6.148: $R_{jd} = R_{sig}(1 + G_m R'_L) + R'_L$

If we try to adapt the above formula for BJTs:

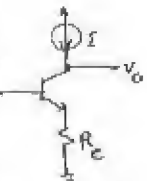
Using Miller's Theorem for C_{μ} , we

would have $C_{\mu}(1 + G_m R'_L)$ hanging

from the base to the ground. V_i

The resistance seen by $C_{\mu}(1 + G_m R'_L)$

is: $R'_{sig} = (R_{sig} + r_x) \parallel R_{in}$



$$R'_{sig} = [R_{sig} + r_x] \parallel R_{in}$$

$$R'_L = R_L \parallel R_{out}$$

From the collector side, the resistance seen

by C_{μ} is $R_{out} \parallel R_L$ or R'_L . Therefore the total

resistance seen by C_{μ} is:

$$R_H = [(R_{sig} + r_x) \parallel R_{in}] (1 + G_m R'_L) + R'_L$$

The resistance seen by C_L is again $R_L \parallel R_o$

or R'_L . $\Rightarrow R'_L = R'_L$ (Same as Eq. 6.150 for

Now the resistance seen by C_{π} is r_{π} in

to

then we can write: $\tau_H = C_{\pi} R_H + C_{\mu} R_H + C_L R'_L$

b) i) $R_o = 0$, $R_{out} = R_o$, $r_{\pi} = \frac{\beta}{g_m} = 5 \text{ k}\Omega$

$$A_H = \frac{-r_{\pi}}{r_{\pi} + R_{sig} + r_x} \approx g_m R'_L \quad \text{Eq. (6.70)}$$

$$R'_L = R_L \parallel R_{out}, \text{ since } R_{out} \ll R_o \text{ then } R'_L = R_L \parallel R_o$$

$$R_o = r_o (1 + g_m R'_c) = r_o (1 + g_m r_{\pi}) = (\beta + 1) r_o = 101 \text{ M}\Omega$$

$$R'_L = 5.3 \text{ k}\Omega \parallel 101 \text{ M}\Omega = 5.3 \text{ k}\Omega \Rightarrow A_H = \frac{-5}{5 + 1 + 0.2} \times 20 \times 5.3$$

Now using formulas given in part (a) we can't

$$f_H = \frac{1}{2\pi \tau_H}. \text{ Since } R_{out} \ll R_o, \text{ then } R'_L = 5.3 \text{ k}\Omega =$$

Note that for $R_o = 0$, we have $R_{in} = r_{\pi} = 5$

and $G_m = g_m = 20 \text{ mA/V}$

Cont

$$R_M = (R_{sig} + r_x) \parallel r_{\pi} (1 + g_m R'_L) + R'_L$$

$$R_M = ((1 + 0.2) \parallel 5) (1 + 20 \times 5.3) + 5.3 = 108.85 \text{ k}\Omega$$

$$R_{\pi} = r_{\pi} \parallel (R_{sig} + r_x) = 5 \text{ k}\Omega \parallel 1.2 \text{ k}\Omega = 0.97 \text{ k}\Omega$$

$$\tau_H = R_{\pi} C_{\pi} + R_M C_M + R'_L C_L = 10 \times 0.97 + 0.5 \times 108.85 + 2 \times 5.3$$

$$\tau_H = 74.73 \text{ ns} \Rightarrow f_H = 213 \text{ MHz}, A_H = -85.5 \text{ V/V}$$

ii) $R_E = 200 \Omega$.

$$A_{V0} \approx -g_m r_o \quad (\text{Eq. 6.159})$$

$$A_{V0} = -20 \times 100 = -2000 \text{ V/V}$$

$$R_{in} = (\beta + 1) r_e + (\beta + 1) R_E \frac{1}{1 + R_E / r_o}$$

$$R_{in} = 5 \text{ k}\Omega + 101 \times 0.2 \times \frac{1}{1 + \frac{5.3}{100}} = 24.18 \text{ k}\Omega$$

$$R_o \approx (1 + g_m R'_E) r_o$$

$$R'_E = R_E \parallel r_{\pi}$$

$$R_o = (1 + 20(5 \text{ k}\Omega \parallel 0.2 \text{ k}\Omega)) \times 100 \text{ k}\Omega = 484.6 \text{ k}\Omega$$

$$G_v = \frac{R_{in}}{R_{in} + R_{sig}} A_{V0} \frac{R_L}{R_L + R_o} = \frac{24.18}{24.18 + 1} \frac{2000}{24.18 + 1} \frac{5.3}{5.3 + 484.6}$$

$$G_v = -20.78 \text{ V/V} = A_H$$

Now to calculate f_H .

$$R'_L = R_L \parallel R_{out}, R_{out} = R_o = 484.6 \text{ k}\Omega$$

$$R'_L = 5.3 \parallel 484.6 = 5.24 \text{ k}\Omega = R_{CL}$$

$$G_m = \frac{g_m}{1 + g_m R_E} = \frac{20}{1 + 20 \times 0.2} = 4 \text{ mA/V}$$

$$R_M = (R_{sig} + r_x) \parallel r_{\pi} (1 + G_m R'_L) + R'_L$$

$$R_M = (1.2 \text{ k}\Omega \parallel 24.18 \text{ k}\Omega) (1 + 4 \times 5.24) + 5.24 = 30.35 \text{ k}\Omega$$

$$R_M = 30.35 \text{ k}\Omega$$

$$R_{\pi} = r_{\pi} \parallel \frac{R_{sig} + r_x + R_E}{1 + g_m R_E \left(\frac{r_o}{r_o + R'_L} \right)} = 5 \text{ k}\Omega \parallel \frac{1 + 0.2 + 0.2}{1 + 20 \times 0.2 \times \frac{100}{105.3}}$$

$$R_{\pi} = 0.275 \text{ k}\Omega$$

$$\tau_H = 0.275 \times 10 + 30.35 \times 0.5 + 5.24 \times 2 = 28.42 \text{ ns}$$

$$f_H = 5.6 \text{ MHz}, A_H = -20.78 \text{ V/V}$$

6.117

a) $I = \frac{1}{2} K_n \frac{W}{L} V_{ov}^2 = \frac{1}{2} \times 160 \times 100 \times (0.5)^2 = 2 \text{ mA}$

b) $g_m = \frac{2I_D}{V_{ov}} = \frac{2 \times 2}{0.5} = 8 \text{ mA/V}$

$$g_{mb} = \chi g_m = 0.2 \times 8 = 1.6 \text{ mA/V}$$

$$r_o \approx \frac{1}{\lambda I_D} = \frac{1}{0.05 \times 2} = 10 \text{ k}\Omega$$

c) Using Eq. 6.167: $A_{V0} = \frac{g_m r_o}{1 + (g_m + g_{mb}) r_o}$

$$A_{V0} = \frac{8 \times 10}{1 + (8 + 1.6) \times 10} = 0.82 \text{ V/V}$$

If we use the approximation formula

Eq. 6.168: $A_{V0} = \frac{1}{1 + \chi} = 0.83 \text{ V/V}$

$$R_o = \frac{1}{g_m + g_{mb}} \parallel r_o = \frac{1}{8 + 1.6} \text{ k}\Omega \parallel 10 \text{ k}\Omega = 103 \Omega$$

d) with $R_L = 1 \text{ k}\Omega$

$$A_v = \frac{g_m R'_L}{1 + g_m R'_L} \quad (\text{Eq. 6.166})$$

$$R'_L = R_L \parallel r_o \parallel \frac{1}{g_{mb}} = 1 \text{ k}\Omega \parallel 10 \text{ k}\Omega \parallel \frac{1}{1.6} \text{ k}\Omega = 370 \Omega$$

$$A_v = \frac{8 \times 370 \times 10^{-3}}{1 + 8 \times 0.370} = 0.75 \text{ V/V}$$

6.118

$$R_o = r_o \parallel \frac{1}{g_m + g_{mb}} = 20 \text{ k}\Omega \parallel \frac{1}{5 + 1} = 20.17 \text{ k}\Omega$$

$$A_H = \frac{V_o}{V_{sig}} = G_v = A_{V0} \frac{R_L}{R_L + R_o} = \frac{g_m r_o}{1 + (g_m + g_{mb}) r_o} \frac{R_L}{R_L + R_o}$$

$$A_H = \frac{5 \times 20}{1 + (5 + 1) 20} \times \frac{20 \text{ k}\Omega}{20 \text{ k}\Omega + 20.17 \text{ k}\Omega} = 0.41 \text{ V/V}$$

$$f_2 = \frac{g_m}{2\pi C_{gs}} \quad (\text{Eq. 6.172}) \Rightarrow f_2 = \frac{5}{2\pi \times 2} = 398 \text{ MHz}$$

$$R_{gd} = R_{sig} = 20 \text{ k}\Omega$$

$$R_{gs} = \frac{R_{sig} + R'_L}{1 + g_m R'_L}, R'_L = R_L \parallel r_o \parallel \frac{1}{g_{mb}} = 20 \text{ k}\Omega \parallel 20 \text{ k}\Omega \parallel \frac{1}{1}$$

$$R_{gs} = \frac{20 + 0.91}{1 + 5 \times 0.91} = 3.77 \text{ k}\Omega$$

$$R_{CL} = R_L \parallel R_o = 20 \text{ k}\Omega \parallel 20.17 = 10.04 \text{ k}\Omega$$

$$\tau_H = C_{gd} R_{gd} + C_{gs} R_{gs} + C_L R_{CL}$$

$$\tau_H = 0.1 \times 20 \text{ k}\Omega + 2 \times 3.77 + 1 \times 10.04 = 19.58 \text{ ns}$$

$$f_H = \frac{1}{2\pi \tau_H} = 8.13 \text{ MHz}$$

Contribution of each capacitor time constant to the overall τ_H is:

10.2% for C_{gd} , 38.5% for C_{gs} , 51.3% for C_L .

6.119

$$R_{gd} = R_{sig}, R_{gs} = \frac{R_{sig} + R'_L}{1 + g_m R'_L} \approx \frac{R_{sig}}{1 + g_m R'_L} \text{ if } R_{sig} \gg R'_L$$

$$\tau_H = R_{gd} C_{gd} + R_{gs} C_{gs} + C_L R_{CL}$$

$$\tau_H \approx R_{sig} \left(C_{gd} + \frac{C_{gs}}{1 + g_m R'_L} \right) \Rightarrow f_H \approx \frac{1}{2\pi R_{sig} \left(C_{gd} + \frac{C_{gs}}{1 + g_m R'_L} \right)}$$

R_{CL} is ignored and $R'_L = R_L \parallel r_o \parallel \frac{1}{g_{mb}}$

$f_H \propto (1 + g_m R'_L)$ Therefore f_H can be increased

Cont.

by increasing $g_m R'_L$. We also know that $R'_L = R_L \parallel r_o \parallel \frac{1}{g_{mb}}$ and hence $R'_L \leq \frac{1}{g_{mb}}$ or $g_m R'_L \leq \frac{g_m}{g_{mb}} = \frac{1}{\alpha} \Rightarrow g_m R'_L \leq \frac{1}{\alpha}$. Therefore maximum

f_H can be achieved when we have $g_m R'_L = \frac{1}{\alpha}$:

$$f_H = \frac{1}{2\pi R_{sig}(C_{gd} + \frac{C_{gs}}{1+\frac{1}{\alpha}})} = \frac{1}{2\pi R_{sig}(C_{gd} + \frac{\alpha C_{gs}}{\alpha+1})}$$

For the source follower specified in Problem

$$6.118: f_H = \frac{1}{2\pi \times 20k(0.1 + \frac{0.2 \times 2}{1+0.2})} = 18.37 \text{ MHz}$$

$$\alpha = \frac{g_m}{g_{mb}} = 0.2$$

6.120

Using Eq. 6.178: $f_z = \frac{1}{2\pi C_H r_c}$

$$g_m = \frac{I_D}{V_T} = \frac{2}{0.025} = 200 \text{ mA/V}$$

$$r_{\pi} = \frac{\beta}{g_m} = \frac{100}{200} = 0.5 \text{ k}\Omega$$

$$r_c = \frac{r_{\pi}}{\beta+1} = \frac{0.5 \text{ k}\Omega}{100+1} = 4.95 \Omega$$

$$f_T = \frac{g_m}{2\pi(C_{\pi} + C_{\mu})} \Rightarrow (C_{\pi} + C_{\mu}) = \frac{200 \text{ m}}{2\pi \times 800 \text{ M}} = 39.8 \text{ pF}$$

$$C_{\pi} = 39.8 - 2 = 37.8 \text{ pF}$$

$$f_z = \frac{1}{2\pi \times 37.8 \times 4.95 \times 10^{-12}} = 851 \text{ MHz}$$

From Table 5.6: $A_M = \frac{r_o \parallel R_L}{\frac{R_{sig} + r_{\pi} + r_c}{\beta+1} + r_o \parallel R_L}$

$$A_M = \frac{20k \parallel 1k}{\frac{10 + 0.2 + 0.5 + (20k \parallel 1k)}{101}} = 0.95$$

$$A_M = \frac{0.95}{0.11 + 0.95} = 0.9 \text{ V/V}$$

$$R_{\mu} = R_{sig} \parallel (r_{\pi} + (\beta+1)R'_L) \quad (\text{Eq. 6.179})$$

$$R'_{sig} = R_{sig} + r_x = 10 + 0.2 = 10.2 \text{ k}\Omega$$

$$R'_L = R_L \parallel r_o = 1k \parallel 20k = 0.95 \text{ k}\Omega$$

$$R_{\mu} = 10.2 \text{ k} \parallel (0.5 + 101 \times 0.95) = 9.22 \text{ k}\Omega$$

$$R_{\pi} = \frac{R'_{sig} + R'_L}{1 + \frac{R'_{sig}}{r_{\pi}} + \frac{R'_L}{r_c}} = \frac{10.2 \text{ k} + 0.95 \text{ k}}{1 + \frac{10.2}{0.5} + \frac{0.95}{0.5} \times 101} = 52.3 \Omega$$

$$f_H = \frac{1}{2\pi(C_{\mu}R_{\mu} + C_{\pi}R_{\pi})} = \frac{1}{2\pi(2 \times 9.22 + 37.8 \times 0.0523)}$$

$$f_H = 7.8 \text{ MHz}$$

6.121

$$g_m = \frac{I_D}{V_T} = \frac{1}{0.025} = 40 \text{ mA/V}, \quad r_c = \frac{\beta}{(\beta+1)g_m} = 25 \Omega$$

$$f_T = \frac{g_m}{2\pi(C_{\pi} + C_{\mu})} = 20 \text{ MHz} \Rightarrow C_{\pi} + C_{\mu} = 3.18 \text{ pF}$$

$$C_{\mu} = 0.1 \text{ pF} \Rightarrow C_{\pi} = 3.08 \text{ pF}$$

$$r_{\pi} = \frac{\beta}{g_m} = 2.5 \text{ k}\Omega$$

$$r_o = \frac{V_A}{I_D} = \frac{20}{1} = 20 \text{ k}\Omega$$

r_o is in effect parallel to R_L , so $R'_L = R_L \parallel r_o$

$$R'_L = 1k \parallel 20k = 0.95 \text{ k}\Omega. \quad \text{From Table 5.6:}$$

$$A_M = \frac{R'_L}{\frac{R_{sig} + r_{\pi} + r_c}{\beta+1} + R'_L} = \frac{0.95}{\frac{1 + 2.5 + 0.1 + 0.95}{101}} = 0.96$$

$$R_{\mu} = R_{sig} \parallel (r_{\pi} + (\beta+1)R'_L) \quad (\text{Eq. 6.179})$$

$$R'_{sig} = R_{sig} + r_x = 1 + 0.1 = 1.1 \text{ k}\Omega$$

$$R_{\mu} = 1.1 \text{ k} \parallel (2.5 \text{ k} + 101 \times 0.95) = 1.08 \text{ k}\Omega$$

$$R_{\pi} = \frac{R'_{sig} + R'_L}{1 + \frac{R'_{sig}}{r_{\pi}} + \frac{R'_L}{r_c}} = \frac{1.1 + 0.95}{1 + \frac{1.1}{2.5} + \frac{0.95}{0.025}} = 0.052 \text{ k}\Omega$$

$$f_H = \frac{1}{2\pi C_{\mu} R_{\mu}} = \frac{1}{2\pi(0.052 \times 1.08 \times 10^3)} = 593.8 \text{ MHz}$$

6.122

$$I_D = 2 \text{ mA} \Rightarrow g_m = \frac{2}{0.025} = 80 \text{ mA/V}, \quad r_{\pi} = \frac{\beta}{g_m} = 1 \text{ k}\Omega$$

$$r_c = \frac{r_{\pi}}{\beta+1} = 12.4 \Omega$$

$$f_T = \frac{g_m}{2\pi(C_{\pi} + C_{\mu})} \Rightarrow C_{\pi} + C_{\mu} = \frac{80 \text{ m}}{2\pi \times 400 \times 10^6} = 31.85 \text{ pF}$$

$$\Rightarrow C_{\pi} = 31.85 - 2 = 29.85 \text{ pF}$$

$$A_M = \frac{R_L}{\frac{R_{sig} + r_{\pi}}{\beta+1} + R_L} = \frac{1}{\frac{R_{sig}}{101} + 0.0124 + 1} = 1.0124$$

$$R'_L = R_L = 1 \text{ k}\Omega, \quad R'_{sig} = R_{sig} + r_x = R_{sig}$$

$$R_{\mu} = R_{sig} \parallel [r_{\pi} + (\beta+1)R'_L] \quad (\text{Eq. 6.179})$$

$$R_{\mu} = R_{sig} \parallel (1.25 + 101 \times 1) = R_{sig} \parallel 102.25 \text{ k}\Omega$$

$$R_{\pi} = \frac{R'_{sig} + R'_L}{1 + \frac{R'_{sig}}{r_{\pi}} + \frac{R'_L}{r_c}} \quad (\text{Eq. 6.180})$$

$$R_{\pi} = \frac{R_{sig} + 1 \text{ k}}{1 + 0.8 \frac{R_{sig}}{1.25} + 80} = \frac{R_{sig} + 1}{0.8 R_{sig} + 81}$$

$$f_H = \frac{1}{2\pi(R_{\pi}C_{\pi} + R_{\mu}C_{\mu})} = \frac{1}{2\pi(29.85 R_{\pi} + 2 R_{\mu})}$$

a) $R_{sig} = 1 \text{ k}\Omega$: $A_M = 0.998 \text{ V/V}$

$$R_{\mu} = 0.99 \text{ k}\Omega, R_{\pi} = 24.4 \Omega \Rightarrow f_H = 58.8 \text{ MHz}$$

b) $R_{sig} = 10 \text{ k}\Omega$: $A_M = 0.9 \text{ V/V}$

$$R_{\mu} = 9.11 \text{ k}\Omega, R_{\pi} = 124 \Omega \Rightarrow f_H = 7.27 \text{ MHz}$$

c) $R_{sig} = 100 \text{ k}\Omega$: $A_M = 0.499 \text{ V/V}$

$$R_{\mu} = 50.6 \text{ k}\Omega, R_{\pi} = 627 \Omega \Rightarrow f_H = 1.34 \text{ MHz}$$

Refer to Fig. P6.123:

Each of the transistors is operating at a bias current of approximately $100\mu\text{A}$. Thus:

$$g_m = \frac{0.1}{0.025} = 4\text{mA/V}, \quad r_{\pi} = \frac{100}{4} = 25\text{k}\Omega$$

$$r_o \approx 250\Omega, \quad r_o = \frac{100}{0.1} = 1\text{k}\Omega$$

$$C_{\pi} + C_{\mu} = \frac{g_m}{2\pi f_T} = \frac{4\text{m}}{2\pi \times 400\text{M}} = 1.59\text{pF} \Rightarrow C_{\pi} + 1.39\text{pF}$$

a) $R_{in} = (1 + \beta) [r_{e1} + (r_{\pi2} \parallel r_{o1})]$

$$R_{in} = 101 [250 \times 10^{-3} + 25\text{k} \parallel 1\text{M}\Omega] \approx 2.5\text{k}\Omega$$

$$A_M = - \frac{R_{in}}{R_{in} + R_{sig}} \times \frac{r_{\pi2} \parallel r_{o1}}{r_{e1} + (r_{\pi2} \parallel r_{o1})} \times g_{m2} r_{o2}$$

$$A_M = - \frac{2.5\text{k}}{2.5\text{k} + 10\text{k}} \times \frac{25\text{k} \parallel 1\text{M}}{0.25 + (25\text{k} \parallel 1\text{M})} \times 4 \times 1\text{M}$$

$$A_M = -3943.6\text{V/V}$$

b) To calculate f_H , refer to Example 6.13:

$$R_{\mu1} = R_{sig} \parallel R_{in} = 10\text{k} \parallel 2.5\text{k} = 1\text{k}\Omega$$

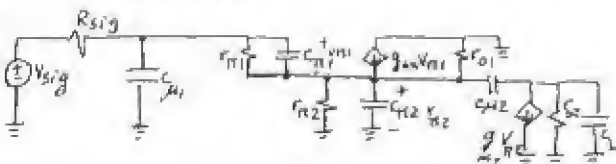
$$R_{in2} = r_{\pi2} \parallel r_{o1}$$

$$R_{in2} = 25\text{k} \parallel 1\text{M}$$

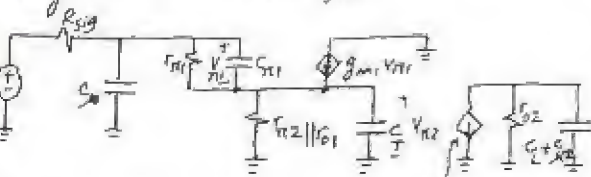
$$R_{in2} = 24.4\text{k}\Omega$$

$$R_{\pi1} = \frac{R_{sig} + R_{in2}}{1 + \frac{R_{sig}}{r_{\pi1}} + \frac{R_{in2}}{r_{e1}}}$$

$$R_{\pi1} = \frac{10 + 24.4}{1 + \frac{10}{25} + \frac{24.4}{0.25}} = 0.35\text{k}\Omega$$



Using Miller's Theorem for $C_{\mu2}$:



$$C_T = C_{\mu2} + C_{\mu2}(1 + g_{m2} r_{o2})$$

$$C_T = 1.39 + 0.2(1 + 4 \times 1000) = 801.6\text{pF}$$

$$R_T = r_{\pi2} \parallel r_{o1} \parallel \frac{r_{\pi1} + R_{sig}}{\beta + 1} = 25\text{k} \parallel 1000\text{k} \parallel \frac{25 + 10}{101}$$

$$R_T = 342\Omega$$

$$R_{\mu2} = r_{o2} = 1000\text{k}$$

$$\tau_H = C_{\mu1} R_{\mu1} + C_{\pi1} R_{\pi1} + C_T R_T + (C_{\mu2} + C_L) R_{\mu2}$$

$$\tau_H = 0.2 \times 10 + 1.39 \times 0.35 + 801.6 \times 0.342 + (0.2 + 1) \times 1000$$

$$\tau_H = 2 + 0.49 + 274.15 + 1200\text{ns}$$

Thus $(C_L + C_{\mu2}) R_{\mu2}$ is the dominating term. The second most significant term is $C_T R_T$.

So $(C_L + C_{\mu2})$ dominates and then C_T or equivalently $C_{\mu2}$.

$$f_H = \frac{1}{2\pi \tau_H} = \frac{1}{2\pi \times 1476.6\text{ns}} = 107.8\text{MHz}$$

c) Increasing the bias currents by a factor of 10:

$$g_m = 40\text{mA/V}, \quad r_{\pi} = 2.5\text{k}\Omega$$

$$r_o \approx 25\Omega, \quad r_o = 100\text{k}\Omega$$

$$C_{\pi} = C_{je} + C_{je} \times 10 = 0.8 + 0.59 \times 10 = 6.7\text{pF}$$

$$C_{\mu} = 0.2\text{pF}$$

$$R_{in} = 101 [0.025 + (2.5\text{k} \parallel 100\text{k})] = 249\text{k}\Omega$$

R_{in} is almost decreased by a factor of 10.

$$A_M = - \frac{249}{249 + 10} \times \frac{2.5\text{k} \parallel 100\text{k}}{0.025 + (2.5\text{k} \parallel 100\text{k})} \times 4000$$

$$A_M = -3807\text{V/V}$$

A_M remains almost constant.

$$C_T = 6.7 + 0.2(1 + 40 \times 100) = 806.9 \text{ (almost constant)}$$

$$R_{\mu1} = R_{sig} \parallel R_{in} = 10\text{k} \parallel 249\text{k} = 9.61\text{k}\Omega$$

$R_{\mu1}$ stays almost the same.

$$R_T = 2.5\text{k} \parallel 10\text{k} \parallel \frac{2.5 + 10}{101} = 117.8\Omega$$

R_T is almost reduced by a factor of 3.

$$R_{in2} = r_{\pi2} \parallel r_{o1} = 2.44\text{k}\Omega$$

$$R_{\pi1} = \frac{10\text{k} + 2.44}{1 + \frac{10}{2.5} + \frac{2.44}{0.025}} = 120\Omega$$

$R_{\pi1}$ is almost decreased by a factor of 3.

$$R_{\mu2} = r_{o2} = 100\text{k}\Omega \text{ (decreased by a factor of 10)}$$

$$\tau_H = 0.2 \times 9.61 + 6.7 \times 0.120 + 806.9 \times 0.118 + 1.2 \times 100$$

$$\tau_H = 1.92 + 0.8 + 95.2 + 120 = 217.92\text{ns}$$

Thus the dominant effect, that of the output pole, is reduced by a factor of 10.

This occurs because $(C_L + C_{\mu2})$ remains constant while r_{o2} decreases by a factor of 10. The second most significant factor (that due to C_T or $C_{\mu2}$ with Miller effect) also decreases, but only by a factor of 3. The overall result is an increase in f_H .

Cont.

$$f_H = \frac{1}{2\pi\tau_H} = \frac{1}{2\pi \times 217.9 \times 10^{-9}} = 730.3 \text{ KHz}$$

f_H has increased by a factor of nearly 7.
Significant increase!

6.124

Note: Although rather long, this is an excellent problem with considerable educational value.

a) DC-Bias

$$\text{For } Q_1: I_{D1} = \frac{1}{2} K'_n \frac{W}{L} (V_{GS1} - V_{t1})^2$$

$$0.1 = \frac{1}{2} \times 2 (V_{GS1} - 1)^2$$

$$\Rightarrow V_{GS1} = 1.316 \text{ V}$$

$$I_{D1} \approx 0.1 \text{ mA}$$

$$I_{C2} \approx 1 \text{ mA}$$

see analysis

b) For Q_1 : $g_{m1} = \sqrt{2\mu_n K'_n \frac{W}{L} I_{D1}} = \sqrt{2 \times 2 \times 0.1} = 0.63 \text{ mA/V}$

For Q_2 : $g_{m2} = 40 \text{ mA/V}$ $r_{\pi 2} = \frac{200}{40} = 5 \text{ k}\Omega$

$$C_{\pi 1} + C_{\mu 1} = \frac{g_{m1}}{2\pi f_T} = \frac{0.63 \times 10^{-3}}{2\pi \times 600 \times 10^6} = 10.6 \text{ pF}$$

Since $C_{\mu 1} = 0.8 \text{ pF} \Rightarrow C_{\pi 1} = 9.8 \text{ pF}$

c) at midband:

$$\frac{V_{\pi 1}}{V_i} = \frac{6.8 \parallel 15}{(6.8 \parallel 15) + \frac{1}{g_{m1}}}$$

$$\frac{V_{\pi 1}}{V_i} = \frac{2.88}{2.88 + \frac{1}{0.63}}$$

$$\frac{V_{\pi 1}}{V_i} = 0.64 \text{ V/V}$$

$$\frac{V_{\pi 2}}{V_{\pi 1}} = -g_{m2} V_{\pi 1} (1 \text{ k} \parallel 3 \text{ k}) \text{ where we have neglected the effect of } R_G.$$

$$\frac{V_{\pi 2}}{V_{\pi 1}} = -40 \times \frac{3}{4} V_{\pi 1} = -30 V_{\pi 1} \Rightarrow \frac{V_{\pi 2}}{V_i} = 0.64 \times (-30) = -19.2 \text{ V/V}$$

$$\frac{V_{\pi 2}}{V_i} = -19.2 \text{ V/V}$$

$$R_{in} = \frac{R_G}{1 - \frac{V_{\pi 2}}{V_{\pi 1}}} = \frac{10 \text{ M}}{1 - (-19.2)} = 495 \text{ k}\Omega$$

$$\frac{V_o}{V_{sig}} = \frac{R_{in}}{R_{sig} + R_{in}} \times \frac{V_{\pi 2}}{V_i} = \frac{495}{495 + 100} \times (-19.2) = -16 \text{ V/V}$$

d) At low frequencies:

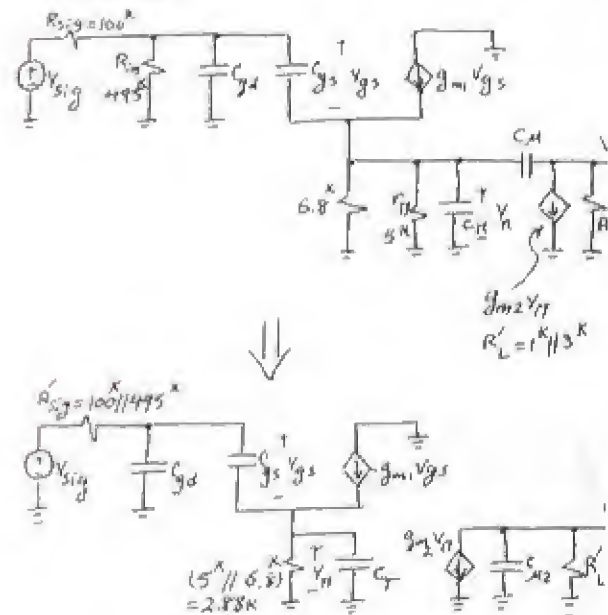
$$C_1 \rightarrow f_{P1} = \frac{1}{2\pi \times 0.1 \times 10^{-6} \times (100 + 495) \times 10^3} = 2.7 \text{ Hz}$$

$$C_2 \rightarrow f_{P2} = \frac{1}{2\pi \times 1 \times 10^{-6} (3+1) 10^{-5}} = 40 \text{ Hz}$$

Thus $f_L \approx 40 \text{ Hz}$

e) At high frequencies:

The high frequency equivalent circuit is as follows:



$$C_T = C_{\pi 1} + C_{\mu 1} (1 + g_{m2} R'_L) = 9.8 + 0.8 (1 + 40 \times \frac{3}{4}) = 34.6 \text{ pF}$$

$$R_{gs1} = R_{sig} \parallel 100 \text{ k} \parallel 495 \text{ k} = 83.2 \text{ k}\Omega$$

$$R_{gs2} = \frac{R_{gs1} + (6.8 \text{ k} \parallel 15 \text{ k})}{1 + g_{m1} (6.8 \text{ k} \parallel 15 \text{ k})} = \frac{83.2 + 2.88}{1 + 0.63 \times 2.88} = 30.6 \text{ k}\Omega$$

$$R_T = 6.8 \parallel 15 \parallel \frac{1}{g_{m1}} = 1 \text{ k}\Omega$$

$$R'_L = 0.75 \text{ k}\Omega$$

$$C_H = C_{gs1} + C_{gs2} R_{gs1} + C_T R_T + C_{\mu 1} R'_L$$

$$C_H = 1 \times 83.2 + 1 \times 30.6 + 34.6 \times 1 + 0.8 \times 0.75 = 149 \text{ pF}$$

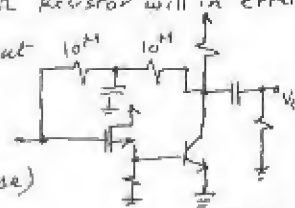
$$f_H \approx \frac{1}{2\pi\tau_H} = 1.07 \text{ MHz}$$

f) There will no longer be a signal feedback

The left hand side $10 \text{ M}\Omega$ resistor will in effect appear between the input terminal and ground,

Thus: $R_{in} = 10 \text{ M}\Omega$

(a factor of 20 increase)



Cont.

and correspondingly A_M becomes:

$A_M = \frac{10}{10.1} \times (-19.2) = -19 \text{ V/V}$ (an increase from -16 V/V)
 Now R_{sig} becomes approximately $100 \text{ k}\Omega$, as compared to $83.2 \text{ k}\Omega$, and correspondingly R_{gd} becomes $100 \text{ k}\Omega$, and R_{gs} becomes $36.6 \text{ k}\Omega$ while R_f and R_L remain practically unchanged.
 Thus f_H becomes 172.5 kHz and f_H decreases from 1.07 MHz to 0.92 MHz .

6.125

Refer to Fig. P6.125:

$$I_{E2} = 10 \text{ mA} \Rightarrow r_{e2} = 2.5 \Omega, r_{\pi2} = 253 \Omega$$

$$I_{E1} = \frac{10}{101} \approx 0.1 \text{ mA} \Rightarrow r_{e1} = 250 \Omega, r_{\pi1} = 25.3 \text{ k}\Omega$$

$$R_{in} = 101 \times [0.25 + 101(0.0025 + 1)] = 10.3 \text{ M}\Omega$$

$$R_{in} = 10.3 \text{ M}\Omega$$

$$R_{out} = r_{e2} + \frac{1}{\beta_2 + 1} \left[r_{e1} + \frac{R_{sig}}{\beta_1 + 1} \right]$$

$$R_{out} = 2.5 + \frac{1}{101} \left[250 + \frac{100000}{101} \right] = 14.8 \Omega$$

Neglecting r_o :

$$A_{v0} = 1000 \text{ V/V}, A_v = \frac{1 \times 1000}{14.8 + 1000} = 0.985 \text{ V/V}$$

6.126

$$I_1 = I_2 = I = 1 \text{ mA} \Rightarrow g_m = 40 \text{ mA/V}, r_{\pi} = \frac{120}{40} = 3 \text{ k}\Omega$$

$$r_e = \frac{3}{121} \approx 25 \Omega, C_{\pi} + C_{\mu} = \frac{g_m}{2\pi f_T} = \frac{40 \text{ mA/V}}{2\pi \times 100 \text{ MHz}} = 9.1 \text{ pF}$$

Using Eq. 6.185:

$$A_M = \frac{V_o}{V_{sig}} = \frac{1}{2} \left(\frac{R_{in}}{R_{in} + R_{sig}} \right) g_m R_L \quad C_{\pi} = 8.6 \text{ pF}$$

$$R_{in} = 2r_{\pi} = 2 \times 3 \text{ k}\Omega = 6 \text{ k}\Omega$$

$$A_M = \frac{1}{2} \times \frac{6}{6 + 20} \times 40 \times 10^3 = 46.15 \text{ V/V}$$

$$f_{p1} = \frac{1}{2\pi \left(\frac{C_{\pi}}{2} + C_{\mu} \right) (R_{sig} \parallel 2r_{\pi})} = \frac{1}{2\pi \left(\frac{8.6}{2} + 0.5 \right) (20 \text{ k} \parallel 6 \text{ k})}$$

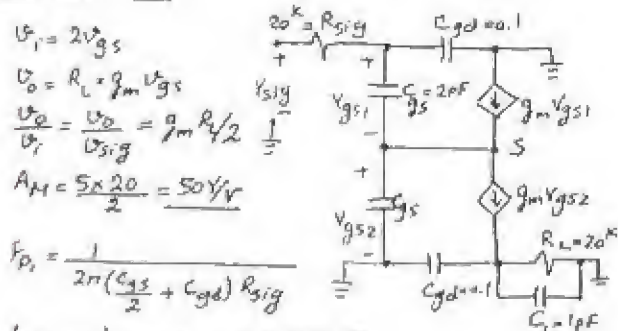
$$f_{p1} = 7.19 \text{ MHz}$$

$$f_{p2} = \frac{1}{2\pi C_{\mu} R_L} = \frac{1}{2\pi \times 0.5 \times 10^4} = 31.8 \text{ MHz}$$

$$f_H = \frac{1}{\sqrt{\left(\frac{1}{f_{p1}} \right)^2 + \left(\frac{1}{f_{p2}} \right)^2}} = 7.01 \text{ MHz}$$

(For f_{p1} and f_{p2} formulas, refer to Eq. 6.186 and 6.187)

6.127



$$f_{p1} = \frac{1}{2\pi \left(\frac{C_{gs}}{2} + C_{gd} \right) R_{sig}}$$

$$f_{p1} = \frac{1}{2\pi (1 + 0.1) 20 \text{ k}} = 7.24 \text{ MHz}$$

$$f_{p2} = \frac{1}{2\pi (C_{gs} + C_L) R_L} = \frac{1}{2\pi (0.1 + 1) \times 20 \text{ k}} = 7.24 \text{ MHz}$$

$$f_H = \frac{1}{\sqrt{\left(\frac{1}{f_{p1}} \right)^2 + \left(\frac{1}{f_{p2}} \right)^2}} = 5.12 \text{ MHz}$$

6.128

All the transistors in this problem are operating at a bias current of 0.5 mA and thus have:

$$r_e = 50 \Omega, g_m = 20 \text{ mA/V}, r_{\pi} = 5 \text{ k}\Omega$$

$$C_{\pi} + C_{\mu} = \frac{20 \text{ mA/V}}{2\pi \times 400 \text{ MHz}} = 8 \text{ pF}$$

$$\text{Since } C_{\mu} = 2 \text{ pF} \Rightarrow C_{\pi} = 6 \text{ pF}, r_o = \infty, r_x = 0$$

a) Common-Emitter amplifier:

$$R_{sig} = 10 \text{ k}\Omega, R_L = 10 \text{ k}\Omega$$

$$A_M = -\frac{r_{\pi}}{R_{sig} + r_{\pi}} g_m R_L = -\frac{5}{10 + 5} 20 \times 10 = -66.7 \text{ V/V}$$

$$f_H = \frac{1}{2\pi (R_{sig} \parallel r_{\pi}) [C_{\pi} + (1 + g_m R_L) C_{\mu}]}$$

$$f_H = \frac{1}{2\pi (10 \text{ k} \parallel 5 \text{ k}) [6 + (1 + 20 \times 10) 2]} = 117 \text{ kHz}$$

b) Cascode:

$$A_M = -\frac{\beta_1 \times 2 R_L}{R_{sig} + r_{\pi1}} = -\frac{100 \times 0.99 \times 10}{10 + 5} = -66 \text{ V/V}$$

$$\text{Input pole: } f_{p1} = \frac{1}{2\pi (R_{sig} \parallel r_{\pi1}) (C_{\pi1} + 2C_{\mu1})}$$

$$f_{p1} = \frac{1}{2\pi (10 \text{ k} \parallel 5 \text{ k}) (6 + 4)} = 4.77 \text{ MHz}$$

$$\text{output pole: } f_{p3} = \frac{1}{2\pi C_{\mu2} R_L} = \frac{1}{2\pi \times 2 \text{ pF} \times 10 \text{ k}} = 7.96 \text{ MHz}$$

pole at midband node:

$$f_{p2} = \frac{1}{2\pi C_{\pi2} r_{e2}} = \frac{1}{2\pi \times 6 \text{ pF} \times 50} = 530.5 \text{ MHz}$$

Very High
Cont.

$$f_H = \sqrt{\left(\frac{1}{f_{H1}}\right)^2 + \left(\frac{1}{f_{H2}}\right)^2} = 4.1 \text{ MHz}$$

c) CC-CB Cascade (Modified diff. amplifier)

$$A_M = \frac{\beta R_C}{R_{sig} + 2r_{\pi}} = \frac{100 \times 10}{10 + 10} = 50 \text{ V/V}$$

$$\text{Input pole: } f_{p1} = \frac{1}{2\pi(R_{sig} \parallel 2r_{\pi})(C_{\pi/2} + C_{\mu})}$$

$$f_{p1} = \frac{1}{2\pi(10 \parallel 10^4)(3 + 2^9)} = 6.4 \text{ MHz}$$

$$\text{Output pole: } f_{p2} = \frac{1}{2\pi C_{\mu2} R_C} = \frac{1}{2\pi \times 2 \times 10^4} = 7.96 \text{ MHz}$$

$$\text{Thus: } f_H = \frac{1}{\sqrt{\left(\frac{1}{f_{p1}}\right)^2 + \left(\frac{1}{f_{p2}}\right)^2}} = 5 \text{ MHz}$$

d) CC-CE Cascade:

$$A_M = -\frac{(\beta+1)\beta_2 R_C}{R_{sig} + r_{\pi1} + (\beta+1)r_{\pi2}} = -\frac{101 \times 100 \times 10}{10 + 5 + 101 \times 5} = -194 \text{ V/V}$$

Refer to Example 6.13 in:

$$R_{H1} = (R_{sig} \parallel R_{H1}) = 10^4 \parallel (A+1)[r_{e1} + r_{\pi2}]$$

$$R_{H1} = 10^4 \parallel 101 \times [0.05 + 5] = 9.81 \text{ K}\Omega$$

$$R_{H1} = r_{\pi1} \parallel \frac{R_{sig} + r_{\pi2}}{1 + \beta_1} = 5 \parallel \frac{10 + 5}{1 + 200} = 144 \Omega$$

$$R_T = r_{\pi2} \parallel \frac{r_{\pi1} + R_{sig}}{\beta+1} = 5 \parallel \frac{5 + 10}{101} = 144 \Omega$$

$$\text{where } C_T = C_{\pi2} + C_{\mu2}(1 + g_{m2} R_C) = 6 + 2(1 + 200) \\ C_T = 408 \text{ pF}$$

$$R_{\mu2} = R_C = 10 \text{ K}\Omega$$

$$\tau_H = C_{\mu1} R_{H1} + C_{\pi1} R_{H1} + C_T R_T + C_{\mu2} R_{\mu2}$$

$$\tau_H = 2 \times 9.81 + 6 \times 0.144 + 408 \times 0.144 + 2 \times 10$$

$$\tau_H = 19.62 + 0.86 + 58.75 + 20 = 99.23 \text{ ns}$$

$$f_H = \frac{1}{2\pi \tau_H} = \frac{1}{2\pi \times 99.23} = 1.6 \text{ MHz}$$

e) Folded Cascode:

$$A_M = -\frac{\beta_1 \alpha_2 R_C}{R_{sig} + r_{\pi1}} = -\frac{100 \times 0.99 \times 10}{10 + 5} = -66 \text{ V/V}$$

Input pole:

$$f_{p1} = \frac{1}{2\pi(R_{sig} \parallel r_{\pi1})(C_{\pi1} + 2C_{\mu1})} = \frac{1}{2\pi(10 \parallel 5)(6 + 4)}$$

$$f_{p1} = 4.77 \text{ MHz}$$

$$\text{At middle: } f_{p2} = \frac{1}{2\pi C_{\pi2} r_{e2}} = \frac{1}{2\pi \times 6 \times 0.05} = 530 \text{ MHz}$$

$$\text{At output: } f_{p3} = \frac{1}{2\pi C_{\mu2} R_C} = \frac{1}{2\pi \times 2 \times 10} \Rightarrow \text{very high!}$$

$$f_{p3} = 7.96 \text{ MHz}$$

$$\text{Thus: } f_H = \frac{1}{\sqrt{\left(\frac{1}{4.77}\right)^2 + \left(\frac{1}{7.96}\right)^2}} = 4.1 \text{ MHz}$$

f) CC-CB Cascade:

$$A_M = \frac{(\beta+1)\alpha_2 R_C}{R_{sig} + (\beta+1)2r_{\pi}} = \frac{101 \times 0.99 \times 10}{10 + 101 \times 0.1} \approx 50 \text{ V/V}$$

$$\text{Input pole: } f_{p1} = \frac{1}{2\pi(R_{sig} \parallel 2r_{\pi})(C_{\pi/2} + C_{\mu})}$$

$$f_{p1} = \frac{1}{2\pi(10^4 \parallel 10^4)(3 + 2^9)} = 6.4 \text{ MHz}$$

$$\text{Output pole: } f_{p2} = \frac{1}{2\pi R_C C_{\mu}} = \frac{1}{2\pi \times 10^4 \times 2^9} = 7.96 \text{ MHz}$$

$$f_H = \frac{1}{\sqrt{\left(\frac{1}{6.4}\right)^2 + \left(\frac{1}{7.96}\right)^2}} = 5 \text{ MHz}$$

Summary of results:

Configuration	A_M (V/V)	f_H (MHz)	f_H G.B.
a) CE	-66.7	0.117	7.8
b) cascode	-66	4.1	271
c) CC-CB cascode	+50	5.0	250
d) CC-CE cascode	-194	1.6	310
e) Folded cascode	-66	4.1	271
f) CC-CB cascode	+50	5.0	250

6.129

Refer to Fig. 6.58

$$I_{REF} = 80 \mu\text{A} = I_A = I_1 = I_2 = I_3$$

All transistors have the same g_m , $r_o > V_{OV}$ values.

$$I = \frac{1}{2} \mu_n' \frac{W}{L} V_{OV}^2 \Rightarrow 0.08 = \frac{1}{2} \times 4 \times V_{OV}^2 \Rightarrow V_{OV} = 0.2$$

$$V_{GS} = V_{OV} + V_E = 0.2 + 0.5 = 0.7 \text{ V}$$

$$V_{G1} = V_{GS} = 0.7 \text{ V} = V_{S4} \Rightarrow V_{G4} = 0.7 + V_{GS4} = 1.4 \text{ V}$$

$$\Rightarrow V_{G3} = 1.4 \text{ V} \Rightarrow V_{S3} = 1.4 \text{ V} - V_{GS} = 0.7 \text{ V}$$

$$\Rightarrow V_{G2} = V_{O3} = V_{S3} + V_{OV} = 0.9 \text{ V}$$

As explained, the voltage at the gate of Q_3 is $2V_{GS}$ which implies voltage of $V_{GS} = V_{OV} + V_E$ at the source of Q_3 . For minimum allowable voltage, $V_{DS} = V_{OV}$ or equivalently $V_{min} = V_{OV}$

$$V_{min} = V_{OV} + V_{OV} + V_E = 2V_{OV} + V_E$$

$$g_m = \frac{2I_O}{V_{OV}} = \frac{2 \times 0.08}{0.2} = 0.8 \text{ mA/V}$$

$$\text{Using Eq. 6.189: } R_o = r_{o3} + [1 + (g_{m3} + g_{mb3})r_{o3}]r_{o2}$$

$$R_o = 100 \text{ K} + [1 + 0.8 \times 100] \times 100 = 8.2 \text{ M}\Omega$$

6.130

$I_{REF} = 25 \mu A$, Refer to Fig. 6.58

$I_1 = 25 \mu A = I_2$, $W_1 = W_4 = 2 \mu m$, $W_2 = W_3 = 4 \mu m$

$$I_1 = \frac{1}{2} K_n' \frac{W_1}{L_1} V_{OV1}^2 \Rightarrow 25 = \frac{1}{2} \times 200 \times \frac{2}{1} V_{OV1}^2 \Rightarrow V_{OV1} = 0.354 V$$

$$V_{OV1} = V_{OV2} \Rightarrow \frac{I_2}{I_1} = \frac{(W/L)_2}{(W/L)_1} \Rightarrow I_2 = 25 \times \frac{4}{2} = 50 \mu A$$

$$I_2 = 0.5 mA = I_3$$

$$I_0 = 0.5 mA$$

$$V_{GS1} = V_{OV1} + V_t = 0.354 + 0.6 = 0.954 V$$

$$V_{G1} = 0.954 V$$

$V_{G4} = V_{GS1} + V_{GS4}$, Since $I_1 = I_4$ and $W_1 = W_4$ then

$$V_{GS1} = V_{GS4} \Rightarrow V_{G4} = 2V_{GS1} = 1.91 V = V_{G3}$$

The lowest possible voltage for the output is

when Q_3 has $V_{DS3} = V_{OV3}$ or $V_{min} = V_{G3} - V_{GS3} = V_{OV3}$

Since $V_{GS1} = V_{GS2}$ and $I_2 = I_3$ then $V_{GS3} = V_{GS1}$

$$\Rightarrow V_{min} = 1.91 - 0.954 + 0.354 = 1.31 V$$

$$g_{m1} = g_{m3} = \frac{2I_D}{V_{OV}} = \frac{2 \times 0.5}{0.354} = 2.82 mA/V$$

$$r_{o2} = r_{o3} = \frac{V_A}{I_D} = \frac{20}{0.5} = 40 k\Omega$$

$$\text{Eq. 6.189: } R_o = r_{o3} + [1 + (g_{m3} + g_{mb3})r_{o3}]r_{o2}$$

$$R_o = 40 + [1 + 2.82 \times 40] \times 40 = 4.6 M\Omega$$

6.131

In the gate of Q_3 we see a small incremental resistance of approximately $\frac{1}{g_m}$ and since the incremental voltages across R_1, Q_5, Q_6 will be small, we can assume that the gates are grounded. Thus the output resistance will be that of the CG transistor Q_3 which has a resistance $R_o = r_{o2} + (1 + (g_{m2} + g_{mb2})r_{o2})r_{o1}$ in its source. We use Eq. 6.101:

$$R_o = r_{o3} + [1 + (g_{m3} + g_{mb3})r_{o3}]R_o$$

$$R_o = r_{o3} + [1 + (g_{m3} + g_{mb3})r_{o3}][r_{o2} + (1 + (g_{m2} + g_{mb2})r_{o2})r_{o1}]$$

$$R_o = r_{o3} + [g_{m3}r_{o3}][g_{m2}r_{o2}r_{o1}]$$

$$R_o = r_{o3} + g_{m2}g_{m3}r_{o1}r_{o2}r_{o3} = g_{m2}g_{m3}r_{o1}r_{o2}r_{o3}$$

6.132

$$V_X = V_{BE3} + V_{BE1} = 1.4 V$$

If I_{REF} is increased

to 1 mA or equivalently

multiplied by 10, then:

$$\frac{I_{C2}}{I_{C1}} = \frac{I_2 e^{V_{BE2}/V_T}}{I_1 e^{V_{BE1}/V_T}} \Rightarrow 10 = e^{(V_{BE2} - V_{BE1})/V_T}$$

$$V_{BE2} - V_{BE1} = \Delta V_{BE} = V_T \ln 10 = 0.058 V$$

$$\Delta V_{BE} = 0.058 V \Rightarrow \Delta V_X = 2\Delta V_{BE} = 0.116 V$$

Now we calculate I_0 for $V_o = V_X$:

$$I_{REF} \approx I_C = 100 \mu A \Rightarrow V_{BE1} =$$

The actual value of $I_0 = \frac{I_{REF}}{1 + \frac{2}{\beta^2 + \beta}}$

$$\Rightarrow I_0 = \frac{100 \mu A}{1 + \frac{2}{200 + 200}} = 99.995 \mu A \approx \frac{1}{\beta^2 + \beta}$$

$$\frac{\Delta I_0}{I_0} = \frac{0.005}{100} = 5 \times 10^{-5} = 0.005\%$$

6.133

Since $Q_{21}, Q_{22}, \dots, Q_{2n}$ are all matched to Q_1 :
 $I_{01} = I_{02} = \dots = I_{0n} = I_0$
 The emitter of Q_3 supplies the basecurrent for all transistors, so $I_{E3} = \frac{(n+1)I_0}{\beta}$

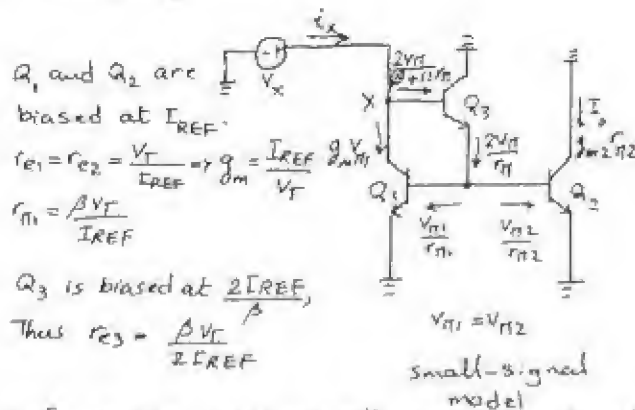
A node equation at the base of Q_3 yields:

$$I_{REF} = I_0 + \frac{(n+1)I_0}{\beta(\beta+1)}, \text{ Thus: } \frac{I_0}{I_{REF}} = \frac{1}{1 + \frac{n+1}{\beta^2}}$$

$$\text{For a deviation from unity of less than } 0.1\%: \frac{99.9}{100} = \frac{1}{1 + \frac{n+1}{\beta^2}} \Rightarrow \frac{n+1}{\beta^2} = \frac{1}{999}$$

$$\Rightarrow n = \frac{\beta^2}{999} - 1 \Rightarrow n \approx 9$$

6.134



Refer to the small-signal analysis performed directly on the circuit. Since the current in the emitter of Q_3 is $\frac{2V_{\pi1}}{r_{\pi1}}$, the voltage $V_{\pi3}$ will be: $V_{\pi3} = \frac{2V_{\pi1}}{r_{\pi1}} \times r_{e3}$.

$V_x = V_{\pi2} + V_{\pi1} = \frac{2V_{\pi1} r_{e3}}{r_{\pi1}} + V_{\pi1} = V_{\pi1} (1 + 2 \frac{r_{e3}}{r_{\pi1}})$

$V_x = V_{\pi1} (1 + 2 \frac{\beta V_T}{2I_{REF}} \times \frac{I_{REF}}{\beta V_T}) = 2V_{\pi1}$

and $i_x \approx g_{m1} V_{\pi1}$. Thus: $R_{in} = \frac{V_x}{i_x} = \frac{2}{g_{m1}} = \frac{2V_T}{I_{REF}}$

For $I_{REF} = 100 \mu A \Rightarrow R_{in} = \frac{2 \times 0.025}{0.1} = 0.5 k\Omega$

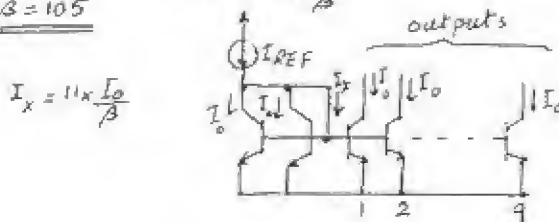
6.135

All the output currents are equal to I_0 , then we have: $I_{REF} = 2I_0 + \frac{11I_0}{\beta} \Rightarrow \frac{I_0}{I_{REF}} = \frac{1}{2 + \frac{11}{\beta}}$

I_0 is ideally $I_{REF}/2$, For 5% lower I_0 :

$0.95 \times \frac{I_{REF}/2}{I_{REF}} = \frac{1}{2 + \frac{11}{\beta}} \Rightarrow \beta = 104.5 \approx 105$

$\beta = 105$



6.136

a) See the analysis on the circuit.

$$I_{REF} = I + \frac{\beta+2}{\beta(\beta+1)} I = I \frac{\beta^2+2\beta+2}{\beta(\beta+1)}$$

$$I_{01} = I_{02} = \frac{1}{2} \frac{\beta+2}{\beta+1} I$$

$$\frac{I_{01}}{I_{REF}} = \frac{I_{02}}{I_{REF}} = \frac{1}{2} \frac{\beta(\beta+2)}{\beta^2+2\beta+2} = \frac{1}{2} \frac{1}{1 + \frac{2}{\beta^2+2\beta}}$$

$$\frac{I_{01}}{I_{REF}} = \frac{1}{2} \frac{1}{1 + \frac{2}{\beta^2}}$$

Observe that the deviation factor $\frac{1}{1 + \frac{2}{\beta^2}}$ is independent of the number of outputs or the value of each output, i.e.:

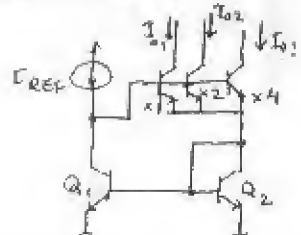
The current I_{REF} can be split into any number of outputs through an appropriate combination of parallel-connected transistors (Q_3 and Q_4 in this case). The reason the error factor remains unchanged at $\frac{1}{1 + \frac{2}{\beta^2}}$ is that the base current that needs to be supplied by I_{REF} (subtracted from I_{REF}) remains unchanged.

b) The 1mA reference current can be used to generate three output currents of 1, 2, 4 mA by using 3 transistors in parallel having relative area ratios of 1, 2, 4 as shown:

$$\frac{I_{01}}{I_{REF}} = \frac{1}{7} \frac{1}{1 + \frac{2}{\beta^2}} \Rightarrow I_{01} = 0.998 \text{ mA (1mA ideally)}$$

$$\frac{I_{02}}{I_{REF}} = \frac{2}{7} \frac{1}{1 + \frac{2}{\beta^2}} \Rightarrow I_{02} = 1.996 \text{ mA (2mA ideally)}$$

$$\frac{I_{03}}{I_{REF}} = \frac{4}{7} \frac{1}{1 + \frac{2}{\beta^2}} \Rightarrow I_{03} = 3.992 \text{ mA (4mA ideally)}$$

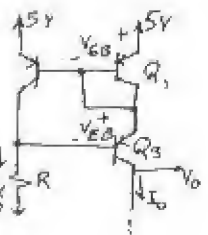


6.137

$$I_{REF} = 0.1 \text{ mA} = \frac{5 - 0.7 - 0.7 - (-5)}{R}$$

$$\Rightarrow R = 86 k\Omega$$

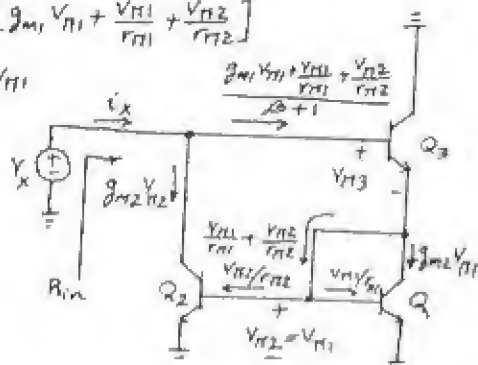
V_{omax} is obtained when Q_3 is saturated: $V_{omax} = 5 - 0.7 - 0.2 = 4.1 \text{ V}$



6.138

$$V_{\pi 3} = r_{e3} \left[g_{m1} V_{\pi 1} + \frac{V_{\pi 1}}{r_{\pi 1}} + \frac{V_{\pi 2}}{r_{\pi 2}} \right]$$

$$V_x = V_{\pi 3} + V_{\pi 1}$$



Small-signal analysis

Note that all 3 transistors are biased at I_{REF}

$$V_x = V_{\pi 3} + V_{\pi 1} = r_{e3} \left[g_{m1} V_{\pi 1} + \frac{V_{\pi 1}}{r_{\pi 1}} + \frac{V_{\pi 2}}{r_{\pi 2}} \right] + V_{\pi 1}$$

$$V_x = (r_{e3} g_{m1} + \frac{r_{e3}}{r_{\pi 1}} + 1) V_{\pi 1}$$

$$V_x = \left(\frac{\beta}{\beta+1} + \frac{2}{\beta+1} + 1 \right) V_{\pi 1} = 2 V_{\pi 1} \left(1 + \frac{1}{\beta+1} \right) \approx 2 V_{\pi 1}$$

$$i_x = g_{m2} V_{\pi 2} + \frac{1}{\beta+1} \left(g_{m1} V_{\pi 1} + \frac{V_{\pi 1}}{r_{\pi 1}} + \frac{V_{\pi 2}}{r_{\pi 2}} \right)$$

$$i_x = V_{\pi 1} \left[g_{m1} + \frac{g_{m1}}{\beta+1} + \frac{g_{m1}}{\beta(\beta+1)} + \frac{g_{m1}}{\beta(\beta+1)} \right]$$

$$i_x \approx g_{m1} V_{\pi 1}$$

$$\text{Thus: } R_{in} = \frac{V_x}{i_x} = \frac{2 V_{\pi 1}}{g_{m1} V_{\pi 1}} = \frac{2}{g_{m1}} = \frac{2 V_T}{I_{REF}}$$

$$\text{For } I_{REF} = 100 \mu A:$$

$$R_{in} = \frac{2 \times 0.025}{0.1} = 0.5 \text{ k}\Omega$$

6.139

$$R_o = \frac{A_{REF}}{2} = \frac{\beta}{2} \frac{V_A}{I_c} = \frac{100}{2} \times \frac{100}{1} = 5 \text{ M}\Omega$$

$$\Delta I_o = \frac{\Delta V_o}{R_o} = \frac{10 \text{ V}}{5 \text{ M}\Omega} = 2 \mu A$$

$$\frac{\Delta I_o}{I_o} = \frac{2 \mu A}{1 \text{ mA}} = 0.2\%$$

6.140

$$I_{REF} = 25 \mu A, I_2 \approx I_{REF} = 25 \mu A$$

$$V_{OV1} = V_{OV2} \Rightarrow \frac{I_1}{I_2} = \frac{W_1}{W_2} \Rightarrow I_1 = 25 \mu A \times \frac{2}{40} = 1.25 \mu A$$

$$I_o = I_3 = I_1 = 1.25 \mu A$$

Refer to Fig. 6.61a

$$V_{OV2} = \frac{I_2}{\frac{1}{2} \mu_n \frac{W}{L}} = \frac{25}{\frac{1}{2} \times 200 \times \frac{40}{1}} = \frac{1}{160} \Rightarrow V_{OV2} = 0.08 \text{ V}$$

$$\Rightarrow V_{GS2} = V_{GS1} = 0.08 + 0.6 = 0.86 \text{ V, therefore}$$

$$V_{G1} = V_{G2} = 0.86 \text{ V}$$

$$V_{OV3} = \frac{I_3}{\frac{1}{2} \mu_n \frac{W}{L}} = \frac{1.25}{\frac{1}{2} \times 200 \times \frac{40}{1}} = \frac{1}{3200} \Rightarrow V_{OV3} = 0.018 \text{ V}$$

$$\text{Therefore } V_{GS3} = 0.018 + 0.6 = 0.618 \text{ V}$$

$$\Rightarrow V_{G3} = V_{S3} + V_{GS3} = 0.86 + 0.618 = 1.48 \text{ V}$$

$$\text{For } V_{Omin}, \text{ we have to have } V_{DS3} = V_{OV3} = 0.018 \text{ V}$$

$$\text{then: } V_{Omin} = V_{G3} + V_{DS3min} = 0.86 + 0.018 = 0.88 \text{ V}$$

$$\text{For } Q_2: g_{m2} = \frac{2I_2}{V_{OV2}} = \frac{2 \times 25 \mu A}{0.08} = 625 \mu A/V = 0.625 \text{ mA/V}$$

$$r_{o2} = \frac{V_A}{I_2} = \frac{20}{0.025} = 800 \text{ k}\Omega$$

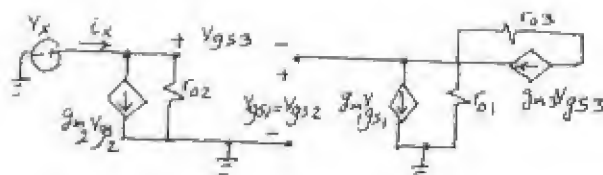
$$\text{For } Q_3: g_{m3} = \frac{2 \times 1.25 \mu A}{0.018} = 139 \mu A/V = 0.139 \text{ mA/V}$$

$$r_{o3} = \frac{20}{0.00125} = 16 \text{ M}\Omega$$

Refer to section 6.12.4 in textbook:

$$R_o = r_{o3} (g_{m3} r_{o2} + 2) = 16 (0.139 \times 800 \text{ k} + 2) = 1811.2 \text{ M}\Omega$$

6.141



$$i_x = g_{m2} V_{GS2} \quad (1)$$

$$V_{GS2} + V_{GS3} = V_x$$

Since Q_2 and Q_3 have the same parameters and same current, therefore $V_{GS2} = V_{GS3}$

$$V_x = 2 V_{GS2} \Rightarrow V_{GS2} = \frac{V_x}{2}$$

Substitute for V_{GS2} in (1):

$$i_x = g_{m2} \times \frac{V_x}{2}$$

$$R_{in} = \frac{V_x}{i_x} = \frac{2}{g_{m2}}$$

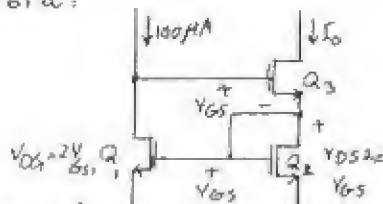
6.142

Refer to Fig. 6.61 a:

$$I_{REF} = 100 \mu A$$

$$V_{DS1} = 2V_{GS}$$

$$V_{DS2} = V_{GS}$$



$$I_{D1} = I_{REF} = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_{th})^2 (1 + \frac{V_{DS1}}{V_A})$$

$$100 = \frac{1}{2} \times 2000 (V_{GS} - 0.6)^2 (1 + \frac{2V_{GS}}{20})$$

$$1 = (V_{GS} - 0.6)^2 (10 + V_{GS})$$

$$V_{GS} = 0.91 V \quad (\text{by iteration})$$

$$I_{D2} = I_{D3} = \frac{1}{2} \times 2000 (V_{GS} - 0.6)^2 (1 + \frac{V_{GS}}{20})$$

$$I_O = 100.47 \mu A$$

Thus there is $\frac{0.47}{100}$ or 0.5% error. Modifying the circuit as Fig. 6.61c ensures that Q_1 and Q_2 have the same V_{DS} and thus eliminate the above error.

6.143

Refer to Fig. 6.62: $I_{REF} = 100 \mu A$ $I_O = 10 \mu A$

$$a) V_{BE1} = 0.7 + V_T \ln \frac{100}{10} = 0.642 V$$

$$V_{BE2} = 0.7 + V_T \ln \frac{10}{1000} = 0.585 V$$

$$I_O = \frac{V_{BE1} - V_{BE2}}{R_E} = 10 \mu A \Rightarrow R_E = 5.7 k\Omega$$

$$b) r_{\pi 2} = (\beta + 1) \frac{V_T}{I_{C2}} = 503 k\Omega \gg R_E$$

$$r_{o2} = \frac{V_A}{I_O} = 10 M\Omega \Rightarrow R_O = (1 + g_{m2} R_E) r_{o2} = 33 M\Omega$$

$$R_O = 33 M\Omega$$

$$\Delta I_O = \frac{\Delta V_{BE}}{R_O} = \frac{5}{R_O} = 0.15 \mu A$$

6.144

$$a) \frac{I_O}{I_{REF}} = 0.9 \Rightarrow I_O = 90 \mu A$$

$$V_{RE} = V_T \ln \frac{1}{0.9} = 2.63 mV$$

$$R_E = \frac{2.63 mV}{90 \mu A} = 29.3 \Omega$$

$$r_o = \frac{V_A}{I_O} = 1.11 M\Omega$$

$$g_m = 3.6 mA/V$$

$$R_O = (1 + g_m R_E) r_o = 1.2 M\Omega \quad \text{Compare to } r_o = 1.11 M\Omega$$

$$b) \frac{I_O}{I_{REF}} = 0.1 \Rightarrow I_O = 10 \mu A$$

$$V_{RE} = V_T \ln 10 = 57.56 mV$$

$$R_E = \frac{57.56 mV}{10 \mu A} = 5.76 k\Omega$$

$$r_o = \frac{100}{10 \mu A} = 10 M\Omega$$

$$g_m = 0.4 mA/V$$

$$R_O = (1 + g_m R_E) r_o = 33 M\Omega \quad \text{Compare to } r_o = 10 M\Omega$$

$$c) \frac{I_O}{I_{REF}} = 0.01 \Rightarrow I_O = 1 \mu A$$

$$V_{RE} = V_T \ln 100 = 115 mV$$

$$R_E = \frac{115}{1} = 115 k\Omega$$

$$r_o = \frac{100}{1} = 100 M\Omega$$

$$g_m = 0.04 mA/V$$

$$R_O = (1 + g_m R_E) r_o = 560 M\Omega \quad \text{Compare to } r_o = 100 M\Omega$$

6.145

$$R_O = [1 + g_m (R_E \parallel r_{\pi})] r_o$$

$$I_E = \frac{0.7 - 0.5}{R_E} = 0.43 mA$$

$$g_m = \frac{I_E}{V_T} = \frac{0.43}{0.025} = 17.2 mA/V$$

$$r_o = \frac{V_A}{I_E} = \frac{100}{0.43} = 232.6 k\Omega$$

$$r_{\pi} = \frac{\beta}{g_m} = \frac{100}{17.2} = 5.8 k\Omega$$

$$R_E = 10 k\Omega$$

$$R_O = [1 + (10^3 / 115.8^3) \times 17.2] \times 232.6$$

$$R_O = 14.92 M\Omega$$



6.146

$$a) I_O = \frac{V_{BE1} + V_{BE2} - V_{BE3}}{R}$$

$$\text{For } I_O = I_{REF}: V_{BE1} = V_{BE2} = V_{BE3} \Rightarrow I_O = \frac{V_{BE1}}{R}$$

$$\text{For } I_O = 10 \mu A: V_{BE} = 0.585 \text{ therefore } R = \frac{58.5}{10} k$$

$$b) g_m = \frac{I_E}{V_T} = \frac{10 \mu A}{0.025} = 0.4 mA/V, r_{\pi} = \frac{\beta}{g_m} = 250 k\Omega$$

$$r_o = \frac{V_A}{I_O} = 10 M\Omega$$

$$R_O = [1 + g_m (R \parallel r_{\pi})] r_o$$

$$R_O = [1 + 0.4 (58.5 / 250^3)] 10^6 = 199.6 M\Omega$$

$$R_O = 200 M\Omega$$

6.147

Q_1 and Q_2 are matched and $I_{O1} = I_{O2} = I$
 therefore $V_{GS1} = V_{GS2}$ and this implies that
 the source of Q_1 and the source of Q_2 have
 the same voltage. Hence: $IR = V_{BE6} = V_T \ln \frac{I}{I_S}$
 $IR = V_T \ln \frac{I}{I_S}$ ①

To find the value of R , first we have to
 calculate I_S .

For $I_E = 1 \text{ mA}$, $V_{BE} = 0.7 \text{ V} \Rightarrow I = I_S e^{0.7/0.025}$
 $\Rightarrow I_S = 6.9 \times 10^{-13} \text{ mA}$

From ①: $R = \frac{V_T \ln \frac{I}{I_S}}{I} = \frac{0.025}{0.010} \ln \frac{0.010}{6.9 \times 10^{-3}}$
 $R = 58.49 \text{ k}\Omega \approx 58.5 \text{ k}\Omega$

Chapter 7 - Problems

7.1

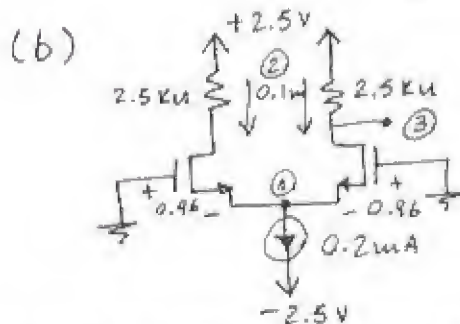
$$V_{DD} = V_{GS} = 2.5V$$

$$K_n' \frac{W}{L} = 3 \frac{mA}{V^2}; V_{tn} = 0.7V$$

$$I = 0.2mA; R_D = 5k\Omega$$

$$(a) V_{ov} = \sqrt{I / K_n' W/L} \\ = \sqrt{0.2/3} = \underline{0.26V}$$

$$V_{GS} = V_{ov} + V_{tn} = 0.26 + 0.7 \\ = \underline{0.96V}$$



$$(1) V_{S1} = V_{S2} = V_{CH} - V_{GS} \\ = 0 - 0.96 = \underline{-0.96V}$$

$$(2) I_{D1} = I_{D2} = \frac{I}{2} = 0.1mA$$

$$(3) V_{D1} = V_{D2} = V_{DD} - \frac{I}{2} \times R_D \\ = +2.5 - 0.1 \times 2.5 = \underline{2.25V}$$

$$(c) \text{ If } V_{cm} = +1V \\ V_{S1} = V_{S2} = +1 - 0.96 = \underline{0.04V} \\ I_{D1} = I_{D2} = \underline{0.1mA} \\ V_{D1} = V_{D2} = \underline{2.25V}$$

$$(d) \text{ If } V_{cm} = -1V \\ V_{S1} = V_{S2} = -1 - 0.96 = \underline{-1.96V} \\ I_{D1} = I_{D2} = \underline{0.1mA} \\ V_{D1} = V_{D2} = \underline{2.25V}$$

$$(e) V_{CMmax} = V_t + V_{DD} - \frac{I}{2} R_D \\ = 0.7 + 2.5 - 0.1 \times 2.5 = \underline{+2.95V}$$

$$(f) V_{CMmin} = -V_{SS} + V_{CS} + V_t + V_{ov} \\ = -2.5 + 0.3 + 0.7 + 0.26 \\ = \underline{-1.24V}$$

$$V_{Smin} = V_{CMmin} - V_{GS} \\ = -1.24 - 0.96 = \underline{-2.2V}$$

7.2

$$(a) V_{ov} = -\sqrt{I / K_p' (W/L)} \\ = -\sqrt{0.7/3.5} = \underline{-0.45V} \\ V_{GS} = V_{ov} + V_{tn} = -0.45 - 0.8 \\ = \underline{-1.25V}$$

$$V_{S1} = V_{S2} = V_G - V_{GS} \\ = 0 + 1.25 = \underline{+1.25V}$$

$$V_{D1} = V_{D2} = \frac{I}{2} \times R_D - V_{DD} \\ = \frac{0.7 \times 2}{2} - 2.5 = \underline{-1.8V}$$

(b) For Q_1 and Q_2 to remain in saturation:

$$V_{DS} \leq V_{GS} - V_t \\ \rightarrow V_{CM} \geq \left(\frac{I}{2} R_D - V_{DD} \right) + V_t$$

$$V_{CMmin} = \frac{0.7 \times 2}{2} - 2.5 - 0.8 \\ = \underline{-2.6V}$$

To allow sufficient voltage for the current source to operate properly:

$$V_{CH} \leq V_{SS} - V_{CS} + (V_t + V_{ov}) \\ \rightarrow V_{CMmax} = 2.5 - 0.5 - 1.25 \\ = \underline{0.75V}$$

7.3

(a) $V_{G2} = 0$, $V_{G1} = V_{id}$
 if $I_{D1} = I_{D2} = I/2 = 0.1 \text{ mA}$
 then $V_{G1} = V_{G2}$
 thus $V_{id} = 0 \text{ V}$.

$$(b) I_{D1} = \frac{I}{2} + \frac{I}{V_{ov}} \cdot \frac{V_{id}}{2}$$

$$\rightarrow V_{id} = \left(\frac{2I_{D1}}{I} - 1 \right) \cdot V_{ov}$$

For $I_{D1} = 0.15 \text{ mA}$

$$V_{id} = \left(\frac{2 \times 0.15 \text{ mA}}{0.2 \text{ mA}} - 1 \right) \times 0.26$$

$$= \underline{0.13 \text{ V}}$$

(c) $I_{D1} = 0.2 \text{ mA}$ and
 $I_{D2} = 0$ (when Q_2 just
 cuts off)
 this occurs at
 $V_{id} = +\sqrt{2} \times V_{ov}$
 $= +\underline{0.367 \text{ V}}$

(d) $I_{D1} = 0.05 \text{ mA}$ } Opposite
 $I_{D2} = 1.50 \text{ mA}$ } case to (b)
 $\rightarrow V_{id} = \underline{-0.13 \text{ V}}$

(e) $I_{D1} = 0$, $I_{D2} = 0.2 \text{ mA}$ when
 Q_1 just cuts off.
 This occurs at $V_{id} = -\sqrt{2} \times V_{ov}$
 $= \underline{-0.367 \text{ V}}$

For each case find V_S , V_{D1} ,
 V_{D2} , $V_{D2} - V_{D1}$

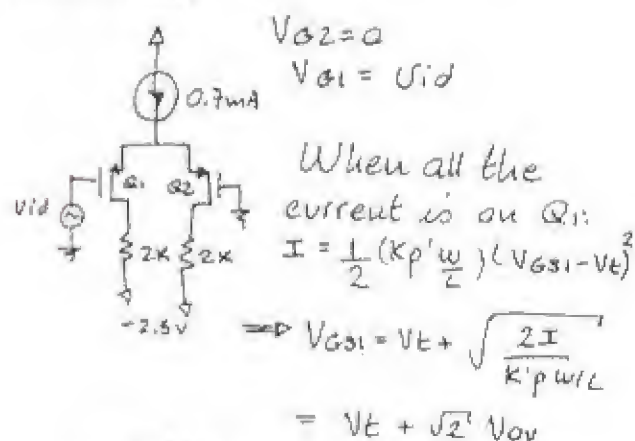
$$V_{GS} = \sqrt{\frac{2 \times I_D}{K_n W/L}} + V_t$$

then $V_S = V_G - V_{GS}$

Solving for each case we
 obtain the following results

V_{id} (V)	I_{D1} (mA)	I_{D2} (mA)	V_S (V)	V_{D1} (V)	V_{D2} (V)	$V_{D2} - V_{D1}$ (V)
(c) +.37	0.2	0	-0.7	1.5	2.5	-1.0
(b) +.13	0.15	0.05	-0.88	1.75	2.25	-0.5
(a) 0	0.1	0.1	-0.96	2	2	0
(d) -.13	0.05	0.15	-1.01	2.25	1.75	+0.5
(e) -.37	0	0.2	-1.07	2.5	1.5	+1.0

7.4



and V_{GS2} is reduced to V_t
 thus $V_S = -V_t$.

Then $V_{id} = V_{GS1} + V_S$
 $= V_t + \sqrt{2} V_{ov} - V_t = \sqrt{2} V_{ov}$

In a similar manner as for
 the NMOS Differential Amplifier,
 as V_{id} reaches $-\sqrt{2} V_{ov}$
 Q_1 turns off and Q_2 on.
 Thus the steering range is
 $\sqrt{2} V_{ov} \leq V_i \leq -\sqrt{2} V_{ov}$

For this particular case
 $\sqrt{2} \times -0.45 \leq V_{id} \leq \sqrt{2} \times 0.45$
 $-0.63 \leq V_{id} \leq 0.63$

When $V_{id} = -0.63 \text{ V}$,
 $I_{D1} = 0.7 \text{ mA}$, $I_{D2} = 0$
 $V_S = -V_{t2} = +0.8 \text{ V}$
 $V_{D1} = 2 \text{ K} \times 0.7 \text{ mA} - 2.5 = -1.1 \text{ V}$
 CONT.

$$V_{D2} = 0 - 2.5V = -2.5V$$

When $V_{id} = +0.63$

$$I_{D1} = 0 ; I_{D2} = 0.7 \text{ mA}$$

$$V_s = V_{id} - V_{GS1} = V_{id} - V_{t1}$$

$$= 0.63 + 0.8 = 1.43$$

$$V_{D1} = -2.5V //$$

$$V_{D2} = -1.1V //$$

7.5

$$V_{G1} = V_{id} \quad I_{D1} = 0.11 \text{ mA}$$

$$V_{G2} = 0 \quad I_{D2} = 0.09 \text{ mA}$$

$$I_D = \frac{1}{2} K'_n \frac{W}{L} (V_{GS} - V_t)^2$$

For Q_1 :

$$0.11 \text{ m} = \frac{1}{2} 3 \text{ m} (V_{GS1} - 0.7)^2$$

$$\rightarrow V_{GS1} = 0.97V$$

For Q_2 :

$$0.09 \text{ m} = \frac{1}{2} 3 \text{ m} (V_{GS2} - 0.7)^2$$

$$\rightarrow V_{GS2} = 0.94V$$

$$V_s = -V_{GS2} = -0.94V$$

$$V_{id} = V_s + V_{GS1} = -0.94 + 0.97$$

$$= 0.03V$$

$$V_{D2} - V_{D1} = 5K(I_{D1} - I_{D2})$$

$$= 5K(0.11 - 0.09) \text{ m}$$

$$= 0.1V$$

thus

$$\frac{V_{D2} - V_{D1}}{V_{id}} = \frac{0.1}{0.03} = 3.33$$

When $I_{D1} = 0.09 \text{ mA}$ and $I_{D2} = 0.11 \text{ mA}$ is the reverse condition from the case we just

studied, thus $V_{id} = -0.03V$

7.6

We know that there is a linear relationship between V_{ov} & V_{id} since:

$$V_{ov} = \frac{V_{id}}{2}$$

Then from the data in table 7.3 we can tell that for

$$V_{i\text{max}} = 150 \text{ mV}$$

$$V_{ov} = 0.2 \times \frac{150}{126} = 0.238V$$

$$\text{For } w/L: \frac{W}{L} = \frac{1}{(V_{ov})^2} \cdot \frac{I}{K}$$

where I and K are constant thus, for w/L :

$$\left(\frac{W}{L}\right)_2 = \frac{50}{\left(\frac{150}{126}\right)^2} = 35.3$$

For g_m : $g_m = \frac{I}{V_{ov}}$ where I is constant

$$\rightarrow g_{m2} = \frac{g_{m1}}{\left(\frac{150}{126}\right)} = \frac{2}{150} = \frac{1.68}{\text{mV}}$$

7.7

$$\left(\frac{V_{id\text{max}}/2}{V_{ov}}\right)^2 = K$$

$$\Rightarrow \underline{2V_{ov}\sqrt{K} = V_{id\text{max}}} \quad \text{Q.E.D}$$

$$I_{D1} = \frac{I}{2} + \left(\frac{I}{V_{ov}}\right) \frac{V_{id}}{2} \sqrt{1-K}$$

CONT.

$$I_{D1} = \frac{I}{2} \pm \frac{I}{V_{OV}} \cdot \frac{2V_{OV}\sqrt{K}}{2} \cdot \sqrt{1-K}$$

$$\rightarrow I_{D1} = \frac{I}{2} \pm I \sqrt{K(1-K)}$$

$$\text{thus } \Delta I = 2I \sqrt{K(1-K)} \quad \text{Q.E.D.}$$

$$\text{For } K = 0.01$$

$$\Delta I = 2I \sqrt{0.01(1-0.01)}$$

$$= 0.198 \times I //$$

$$V_{idmax} = 2V_{OV} \sqrt{0.01} = \underline{0.2V_{OV}}$$

$$\text{For } K = 0.1$$

$$\Delta I = 2I \sqrt{0.1(1-0.1)} = \underline{0.8I}$$

$$V_{idmax} = 2V_{OV} \sqrt{0.2} \\ = \underline{0.894 \cdot V_{OV}}$$

7.8

$$I_D = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_t)^2$$

$$\frac{200}{2} = \frac{1}{2} \times 90 \times \frac{100}{1.6} (V_{GS} - 0.8)^2$$

$$\Rightarrow V_{GS} = \underline{1.19V}$$

$$g_m = \frac{2I_D}{V_{GS} - V_t} = \frac{2 \times 100}{(1.19 - 1)} = \underline{1.06 \text{ mA/V}}$$

$$V_{id} \Big|_{\text{full current switching}} = \sqrt{2} (V_{GS} - V_t) \\ = \underline{0.27V}$$

To double this value, $V_{GS} - V_t$ must be doubled which means that I_D should be quadrupled. i.e. I changed to: 800 μ A

7.9

$$g_m = \frac{2I_D}{V_{OV}} \rightarrow 1 \text{ m} = \frac{I}{0.2}$$

$$\rightarrow I = \underline{0.2 \text{ mA}}$$

$$I_D = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} V_{OV}^2$$

$$100 = \frac{1}{2} \times 90 \times \frac{W}{L} \times (0.2)^2$$

$$\Rightarrow \frac{W}{L} = \underline{55.6}$$

7.10

$$I_D = \frac{1}{2} K_n \frac{W}{L} (V_{GS} - V_t)^2$$

$$50 = \frac{1}{2} \times 400 (V_{GS} - 1)^2$$

$$\Rightarrow V_{GS} = 1.5V$$

$$\text{For } V_{G1} = V_{G2} = 0, V_S = -1.5V$$

$$\text{For } V_{G1} = V_{G2} = 2V, V_S = +0.5V$$

The drain currents are equal in both cases.

$$\text{For } V_{G2} = 0:$$

To reduce I_{D2} by 10%,

$$I_{D2} = 0.9 \times 50 = 45 \mu A$$

$$I_{D1} = 55 \mu A$$

$$V_{GS2} = \sqrt{\frac{2 I_{D2}}{400}} + 1 = 1.47V$$

$$V_{GS1} = \sqrt{\frac{2 \times 55}{400}} + 1 = 1.52V$$

$$\text{Thus, } V_{G1} = V_{GS1} - V_{GS2} = \underline{0.05V}$$

To increase I_{D2} by 10%

$$I_{D2} = 55 \mu A$$

$$I_{D1} = 45 \mu A$$

CONT.

$$V_{GS2} = 1.52V$$

$$V_{GS1} = 1.47V$$

$$\Rightarrow V_{G1} = \underline{\underline{-0.05V}}$$

i_{D2}/i_{D1}	i_{D2} (μA)	i_{D1} (μA)	V_{GS2} (V)	V_{GS1} (V)	$V_G - V_{G1}$ (V)
1	50	50	1.5	1.5	0
0.5	33.3	66.7	1.408	1.577	-0.17
0.9	47.4	52.6	1.487	1.513	-0.026
0.99	47.75	50.25	1.4886	1.5012	-0.013

For $i_{D1}/i_{D2} = 20 \Rightarrow i_{D2} = 4.76 \mu A$
 $i_{D1} = 95.24 \mu A$
 $V_{GS2} = 1.154V, V_{GS1} = 1.690$
 Thus $V_{G1} - V_{G2} = \underline{\underline{0.536V}}$

$$g_m = \frac{I}{V_{ov}} \rightarrow 3 \frac{mA}{V} = \frac{I}{0.316}$$

$$\rightarrow I = \underline{\underline{0.95 mA}}$$

also: $V_{ov} = \sqrt{\frac{I}{K_n' w/L}}$
 $\Rightarrow (0.316)^2 = \frac{0.95 mA}{0.1 \frac{mA}{V^2} \times (\frac{w}{L})}$
 $\rightarrow \frac{w}{L} = \underline{\underline{95}}$

If $R_D = 5K\Omega \Rightarrow$
 $A_d = g_m R_D = 3 \frac{mA}{V} \times 5K\Omega = \underline{\underline{15 \frac{V}{V}}}$
 if $V_{id} = 0.2 \Rightarrow V_{od} = V_{id} \times A_d$
 $= 0.2 \times 15 = \underline{\underline{3V}}$

7.11

$$V_{ov} = \sqrt{\frac{I}{K_n' w/L}} = \sqrt{\frac{0.5}{0.25 \times 50}} = \underline{\underline{0.2V}}$$

$$g_m = \frac{I}{V_{ov}} = \frac{0.5 mA}{0.2V} = \underline{\underline{2.5 \frac{mA}{V}}}$$

$$f_o = \frac{V_A}{I_D} = \frac{10}{(0.5 mA)} = \underline{\underline{40K\Omega}}$$

$$A_d = g_m \times (R_D || f_o)$$

$$= 2.5 \frac{mA}{V} (4K\Omega || 40K\Omega)$$

$$= \underline{\underline{9.09 V/V}}$$

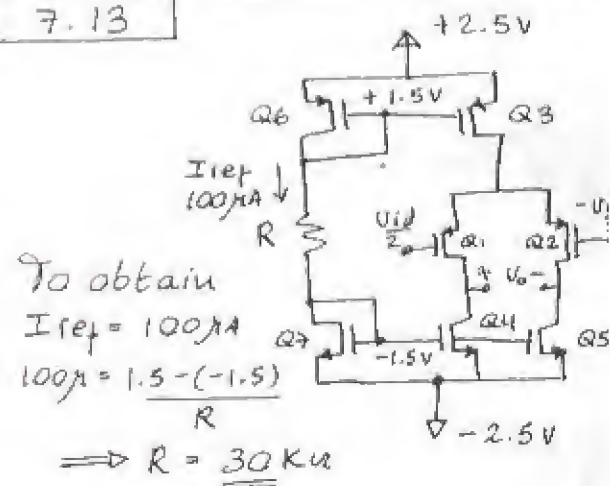
7.12

From Equ. (7.23)

$$\left(\frac{V_{id}/2}{V_{ov}} \right)^2 = 0.1 \rightarrow \left(\frac{0.2/2}{V_{ov}} \right)^2 = 0.1$$

$$\rightarrow V_{ov} = \sqrt{0.1} = \underline{\underline{0.316V}}$$

7.13



$$V_{GS7,4,5} = -1.5 + 2.5 = \underline{\underline{1V}}$$

$$V_{ov7,4,5} = V_{GS} - V_{th} = 1 - 0.7 = \underline{\underline{0.3V}}$$

$$V_{GS6,3} = 1.5 - 2.5 = \underline{\underline{-1V}}$$

$$V_{ov6,3} = -1 - (-0.7) = \underline{\underline{-0.3V}}$$

The differential half circuit is an active-loaded common-source amplifier

CONT

thus, for Q_1, Q_4 :

$$V_{o+} = \frac{V_{id}}{2} g_{m1} (r_{o1} \parallel r_{o4})$$

For Q_2, Q_5 :

$$V_{o-} = -\frac{V_{id}}{2} g_{m2} (r_{o2} \parallel r_{o5})$$

Since $r_{o1} = r_{o2} = r_{o4} = r_{o5} \equiv r_o$

$$V_{o+} - V_{o-} = V_{id} \times g_{m1} \times \frac{r_o}{2}$$

$$\rightarrow \frac{V_{o+} - V_{o-}}{V_{id}} = A_d = g_{m1,2} \times \frac{r_o}{2}$$

$$= \frac{g_{m1,2}}{2} \times \frac{V_{AN}}{I_{D1,2}}$$

$$= \frac{1}{2} \times \frac{2 I_{D1,2}}{V_{ov}} \times \frac{V_{AN}}{I_{D1,2}} = \frac{V_{AN}}{V_{ov1,2}}$$

thus:

$$80 = \frac{20}{|V_{ov1,2}|} \rightarrow V_{ov1,2} = 0.25 \text{ V}$$

phas.

$$\text{Then } V_{GS1,2} = -0.25 - 0.7 \\ = -0.95 \text{ V}$$

We have: $I_{D7} = I_{D6} = 100 \mu\text{A}$

If we choose:

$$I_{D3} = I_{D6} = 100 \mu\text{A} //$$

$$\text{then } I_{D1} = I_{D2} = I_{D4} = I_{D5} = 50 \mu\text{A}$$

To obtain w/L ratios:

$$I_D = \frac{1}{2} \mu_{Cox} (w/L) V_{ov}^2$$

$$\Rightarrow \frac{w}{L} = \frac{2 I_D}{\mu_{Cox} V_{ov}^2}$$

where:

$$\mu_{nCox} = 90 \mu\text{A/V}^2$$

$$\mu_{pCox} = 30 \mu\text{A/V}^2$$

For Q_7 :

$$\left(\frac{w}{L}\right)_7 = \frac{2 \times 100 \mu}{90 \mu \times (0.3)^2} = 24.7$$

For Q_4 and Q_5 :

$$\left(\frac{w}{L}\right)_{4,5} = \frac{2 \times (100 \mu/2)}{90 \mu \times (0.3)^2} = 12.3$$

For Q_1 and Q_2 :

$$\left(\frac{w}{L}\right)_{1,2} = \frac{2 \times (100 \mu/2)}{30 \mu \times (0.25)^2} = 53.3$$

For Q_6 and Q_3 :

$$\left(\frac{w}{L}\right)_{6,3} = \frac{2 \times 100 \mu}{30 \mu \times (0.3)^2} = 74.1$$

In summary, the results are:

	Q_1	Q_2	Q_3	Q_4	Q_5	Q_6	Q_7	
μ_{Cox}	30	30	30	90	90	30	90	$\mu\text{A/V}^2$
I_D	50	50	100	50	50	100	100	μA
V_{ov}	-0.25	-0.25	-0.3	0.3	0.3	-0.3	0.3	V
w/L	53.3	53.3	74.1	12.3	12.3	74.1	24.7	
V_{GS}	-0.95	-0.95	-1	1	1	-1	1	

7.14

$$(a) I_{D1} = \frac{1}{2} K_n' \frac{w}{L} (V_{GS1} - V_t)^2$$

$$I_{D2} = \frac{1}{2} K_n' (2 \times \frac{w}{L}) (V_{GS2} - V_t)^2$$

Since $V_{GS} - V_t$ is equal for both transistors:

$$\Rightarrow \frac{I_{D1}}{I_{D2}} = \frac{1}{2}$$

$$\text{but } I = I_{D1} + I_{D2}$$

$$\Rightarrow 2 I_{D1} = I - I_{D2} \\ I_{D1} = \underline{\underline{I/3}}$$

$$I_{D2} = \underline{\underline{2I/3}}$$

$$(b) V_{ov} = V_{GS} - V_t$$

CONT.

$$V_{ov1} = V_{ov2} = V_{ov}$$

$$\text{For } Q_1: \frac{I}{3} = \frac{1}{2} K_n' \left(\frac{W}{L}\right) V_{ov}^2$$

$$\Rightarrow V_{ov} = \sqrt{\frac{2}{3} \frac{I}{K_n' W/L}}$$

$$(c) g_{m1} = \frac{2I_D}{V_{ov}} \rightarrow g_{m1} = \frac{2I}{3V_{ov}}$$

$$g_{m2} = \frac{4}{3} \frac{I}{V_{ov}}$$

$$V_{o1} = -g_{m1} \times \frac{V_{id}}{2} \cdot R_D$$

$$= -\frac{2}{3} \frac{I}{V_{ov}} \cdot R_D \cdot V_{id}$$

$$V_{o2} = +g_{m2} \times \frac{V_{id}}{2} \cdot R_D$$

$$= \frac{4}{3} \frac{I}{V_{ov}} \cdot R_D \cdot V_{id}$$

$$\Rightarrow \frac{V_{o2} - V_{o1}}{V_{id}} = \left(\frac{4}{3} + \frac{2}{3}\right) \frac{I}{V_{ov}} \cdot R_D$$

$$= \underline{\underline{2 \times \frac{I}{V_{ov}} \cdot R_D}}$$

7.15

$$V_{ov} = \sqrt{\frac{I}{K_n' W/L}} = \sqrt{\frac{0.2}{3}} = 0.26V$$

$$g_m = \frac{I}{V_{ov}} = \frac{0.2mA}{0.26V} = 0.77 \frac{mA}{V}$$

(a) Single-ended output:

From Egn. (7.42)

$$|A_d| = \frac{1}{2} g_m \times R_D = \frac{0.77 \times 10}{2}$$

$$= \underline{\underline{3.85 V/V}}$$

From Egn. (7.41)

$$|A_{cm}| = \frac{R_D}{2R_{ss}} = \frac{10}{2 \times 100} = 0.05 V/V$$

$$CMRR = \frac{|A_d|}{|A_{cm}|} = \frac{3.85}{0.05} = 77$$

i.e. 37.7 dB

(b) Differential output, and
1% mismatch in R_D 's:

$$\text{Egn (7.52)} |A_d| = g_m R_D$$

$$= 0.77 \times 10 = \underline{\underline{7.7 V/V}}$$

$$\text{Egn. (7.51)} |A_{cm}| = \frac{R_D}{2R_{ss}} \times \left(\frac{\Delta R_D}{R_D}\right)$$

$$= \frac{10}{2 \times 100} \times 0.01 = 0.5 mV/V$$

$$CMRR = \frac{|A_d|}{|A_{cm}|} = \frac{7.7}{0.5 \times 10^{-3}} = 15,400$$

i.e. 83.7 dB

7.16

$$V_{ov} = -\sqrt{\frac{I}{K_p' W/L}} = -\sqrt{\frac{0.7mA}{3.5 \frac{mA}{V^2}}}$$

$$= \underline{\underline{-0.45V}}$$

$$g_m = \frac{I}{|V_{ov}|} = \frac{0.7mA}{0.45V} = 1.56 \frac{mA}{V}$$

$$|A_d| = g_m R_D = 1.56 \times 2 = \underline{\underline{3.12 V/V}}$$

$$|A_{cm}| = \frac{R_D}{2R_{ss}} \cdot \left(\frac{\Delta R_D}{R_D}\right) = \frac{2}{2 \times 30} \times 0.02$$

$$= \underline{\underline{6.7 \times 10^{-4}}}$$

$$CMRR = \frac{3.12}{6.7 \times 10^{-4}} = 4680 \rightarrow \underline{\underline{73.4 dB}}$$

7.17

$$(a) I_{D1} = I_{D2} = \frac{1 \text{ mA}}{2} = 0.5 \text{ mA}$$

$$I_D = \frac{1}{2} K_n' \frac{W}{L} V_{OV}^2$$

$$\Rightarrow 0.5 \text{ mA} = \frac{1}{2} \times 2.5 \text{ mA} \times V_{OV}^2$$

$$\rightarrow V_{OV} = 0.632 \text{ V}$$

$$V_{OV} = V_{GS} - V_t = V_{GS} - 0.7$$

$$\rightarrow V_{GS} = 0.632 + 0.7 = 1.332 \text{ V}$$

To obtain 1 mA over $R_{SS} = 1 \text{ k}\Omega$

$$V_S = 1 \text{ mA} \times 1 \text{ k}\Omega = 1 \text{ V}$$

$$\rightarrow V_{CM} = V_S + V_{GS} = 1 + 1.332 = 2.332 \text{ V}$$

$$(b) g_m = \frac{I}{V_{OV}} = \frac{1 \text{ mA}}{0.632 \text{ V}} = 1.6 \frac{\text{mA}}{\text{V}}$$

$$\text{Egn. (7.45): } A_d = g_m \cdot R_D$$

for $A_d = 8 \text{ V/V}$ $R_D = \frac{8}{1.6 \text{ mA/V}} = 5 \text{ k}\Omega$

(c) At the drains:

$$V_{D1} = V_{D2} = 5 \text{ V} - \frac{1 \text{ mA} \times 5 \text{ k}\Omega}{2} = +2.5 \text{ V}$$

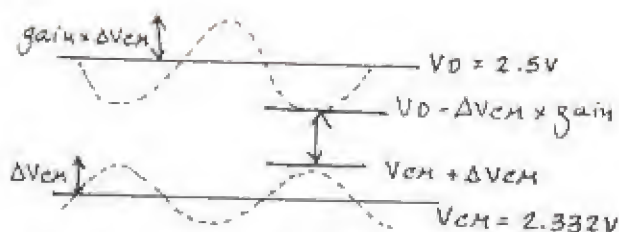
(d) Egn. (7.39):

$$\frac{V_{oi}}{V_{icm}} = \frac{-R_D}{\frac{1}{g_m} + 2R_{SS}}$$

$$\Rightarrow |A_{cm}| = \left| \frac{\Delta V_{oi}}{\Delta V_{icm}} \right| = \frac{5 \text{ k}}{\frac{1}{1.6 \text{ mA/V}} + 2 \times 1 \text{ k}} = 1.9 \text{ V/V}$$

(e) On the edge of the triode region:

$$V_G - V_D = V_t$$



$$\text{If: } V_G - V_D = V_t$$

$$\Rightarrow V_{CM} + \Delta V_{CM} - V_D + \Delta V_{CM} |A_{cm}| = V_t$$

$$\rightarrow 2.332 + \Delta V_{CM} - 2.5 + \Delta V_{CM} \cdot 1.9 = 0.7$$

$$2.9 \Delta V_{CM} = 0.868$$

$$\Delta V_{CM} = 0.3 \text{ V}$$

7.18

$$(a) R_{D1} = R_D + \Delta R/2$$

$$R_{D2} = R_D - \Delta R/2$$

$$g_{m1} = g_m + \Delta g_m/2$$

$$g_{m2} = g_m - \Delta g_m/2$$

The following Egn's are still valid:

$$\text{Egn. (7.62)} \quad i_{D1} = \frac{g_{m1} V_{icm}}{2 g_m R_{SS}}$$

$$\text{Egn. (7.63)} \quad i_{D2} = \frac{g_{m2} V_{icm}}{2 g_m R_{SS}}$$

From which:

$$i_{D1} - i_{D2} = \frac{(g_{m1} - g_{m2}) V_{icm}}{2 g_m R_{SS}} = \frac{\Delta g_m V_{icm}}{2 g_m R_{SS}} \quad (1)$$

$$i_{D1} + i_{D2} = \frac{(g_{m1} + g_{m2}) V_{icm}}{2 g_m R_{SS}}$$

Assuming that Δg_m is small, then

$$g_{m1} + g_{m2} \approx 2 g_m$$

$$\rightarrow i_{D1} + i_{D2} = \frac{2 g_m V_{icm}}{2 g_m R_{SS}} \rightarrow \text{CONT.}$$

$$i_{d1} + i_{d2} = \frac{V_{icm}}{R_{ss}} \quad (2)$$

The differential output is:

$$\begin{aligned} V_{o2} - V_{o1} &= -i_{d2} \cdot R_{o2} + i_{d1} \cdot R_{o1} \\ &= -i_{d2} \left(R_D - \frac{\Delta R_D}{2} \right) + i_{d1} \left(R_D + \frac{\Delta R_D}{2} \right) \\ &= R_D \cdot (i_{d1} - i_{d2}) + \frac{\Delta R_D}{2} (i_{d1} + i_{d2}) \end{aligned}$$

Substituting (1) & (2):

$$= R_D \cdot \frac{\Delta g_m}{2 g_m R_{ss}} \cdot V_{icm} + \frac{\Delta R_D}{2} \frac{V_{icm}}{R_{ss}}$$

From which the common-mode gain is:

$$\begin{aligned} A_{cm} = \frac{V_{o2} - V_{o1}}{V_{icm}} &= \frac{R_D}{2 R_{ss}} \cdot \frac{\Delta g_m}{g_m} \\ &\quad + \frac{\Delta R_D}{2 R_{ss}} \\ &\approx \frac{R_D}{2 R_{ss}} \left[\frac{\Delta g_m}{g_m} + \frac{\Delta R_D}{R_D} \right] \end{aligned}$$

Q.E.D.

(b) For $R_D = 5K\Omega$,
 $R_{ss} = 25K\Omega$

$$\rightarrow A_{cm} = 0.002 V/V$$

For identical R_D 's, this common-mode gain is caused by a mismatch in g_m .

Thus, from Equ. (7.64)

$$\begin{aligned} A_{cm} &= \left(\frac{R_D}{2 R_{ss}} \right) \cdot \left(\frac{\Delta g_m}{g_m} \right) \\ 0.002 &= \frac{5}{2 \times 25} \cdot \frac{\Delta g_m}{g_m} \\ \rightarrow \frac{\Delta g_m}{g_m} &= 0.02 \end{aligned}$$

To reduce A_{cm} to zero, create a mismatch in R_D such as:

$$\begin{aligned} 0 &= \frac{R_D}{2 R_{ss}} \left(\frac{\Delta g_m}{g_m} + \frac{\Delta R_D}{R_D} \right) \\ \Rightarrow \frac{\Delta R_D}{R_D} &= -\frac{\Delta g_m}{g_m} = -0.02 \\ \text{i.e. } &\underline{\underline{-2\% \text{ of } R_D}} \end{aligned}$$

7.19

$$g_m = K_n' \left(\frac{W}{L} \right) \cdot (V_{GS} - V_t)$$

Recalling from calculus that for a function $u = f(x, y)$ the total derivative is:

$$du = \frac{\partial u}{\partial x} \cdot dx + \frac{\partial u}{\partial y} \cdot dy$$

Thus,

$$\begin{aligned} \Delta g_m &= \frac{\partial g_m}{\partial (W/L)} \Delta (W/L) + \frac{\partial g_m}{\partial V_t} \Delta V_t \\ &= K_n' (V_{GS} - V_t) \Delta (W/L) \\ &\quad - K_n' (W/L) \Delta V_t \end{aligned}$$

Thus,

$$\begin{aligned} \frac{\Delta g_m}{g_m} &= \frac{K_n' (V_{GS} - V_t) \Delta (W/L)}{K_n' (W/L) (V_{GS} - V_t)} \\ &\quad - \frac{K_n' (W/L) \Delta V_t}{K_n' (W/L) (V_{GS} - V_t)} \end{aligned}$$

$$\frac{\Delta g_m}{g_m} = \frac{\Delta (W/L)}{(W/L)} + \frac{-\Delta V_t}{(V_{GS} - V_t)}$$

$$\text{but: } V_{GS} - V_t = V_{ov}$$

$$\Rightarrow \frac{\Delta g_m}{g_m} = \frac{\Delta (W/L)}{(W/L)} + \frac{-\Delta V_t}{V_{ov}}$$

Q.E.D.

CONT.

If $\frac{\Delta(W/L)}{W/L} = \pm 0.01$; $\Delta V_t = \pm 5 \text{ mV}$

$V_{ov} = 0.25 \text{ V}$

then, the worst-case fractional mismatch in g_m is:

$$\frac{\Delta g_m}{g_m} = \left| \frac{\Delta(W/L)}{W/L} \right| + \left| \frac{\Delta V_t}{V_{ov}} \right|$$

$$= 0.01 + \frac{0.005}{0.25} = \underline{\underline{0.03}}$$

If: $R_D = 5 \text{ k}\Omega$, $R_{SS} = 25 \text{ k}\Omega$
 $I = 1 \text{ mA}$

From Eqn. (7.64)

$$A_{cm} = \frac{R_D}{2R_{SS}} \cdot \frac{\Delta g_m}{g_m}$$

$$A_{cm} = \frac{5}{2 \times 25} \times 0.03 = \underline{\underline{0.003 \text{ V/V}}}$$

From Eqn. (7.66)

$$CMRR = \frac{2g_m R_{SS}}{\left(\frac{\Delta g_m}{g_m} \right)}$$

where: $g_m = I / V_{ov}$
 $= 1 \text{ mA} / 0.25 \text{ V} = 4 \text{ mA/V}$

$$CMRR = \frac{2 \times 4 \times 25}{0.03} = 6,666.7$$

$\rightarrow \text{i.e. } \underline{\underline{76.5 \text{ dB}}}$

7.20

$V_{BE} = 0.7$ @ $i_c = 1 \text{ mA}$

\rightarrow at $i_c = 0.5 \text{ mA}$ $V_{BE} = -2 \text{ V}$

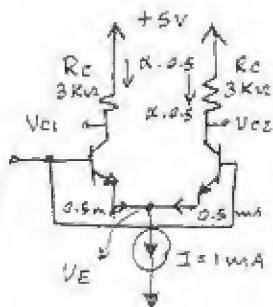
$$V_{BE} = 0.7 + 25 \ln\left(\frac{0.5}{1}\right)$$

$$= 0.683 \text{ V}$$

Thus,

$$V_E = V_{CH} - V_{BE}$$

$$= -2 - 0.683 = \underline{\underline{-2.683 \text{ V}}}$$



$$i_{c1} = i_{c2} = \alpha \times 0.5 = \frac{100}{101} \times 0.5$$

$$= 0.495 \text{ mA}$$

$$V_{c1} = V_{c2} = V_{cc} - i_c R_c$$

$$= 5 - 0.495 \times 3$$

$$= \underline{\underline{+3.515 \text{ V}}}$$

7.21

$$i_{c1} = \alpha I$$

$$= 1 \text{ mA}$$

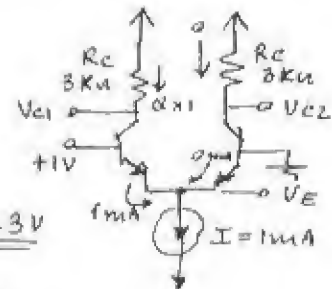
$$V_{BE1} = 0.7 \text{ V}$$

$$V_E = 1 - 0.7 = \underline{\underline{+0.3 \text{ V}}}$$

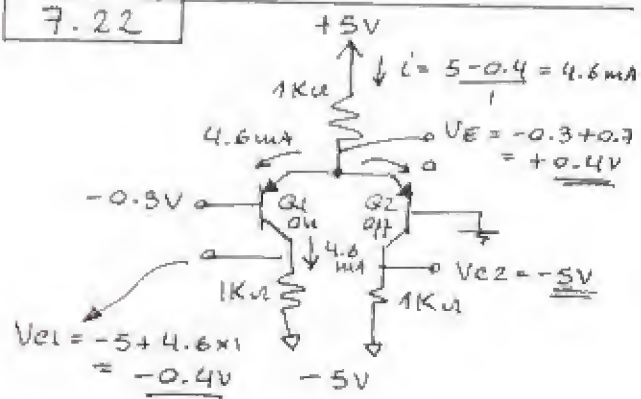
$$V_{c1} = V_{cc} - i_{c1} R_c$$

$$= 5 - 1 \times 3 = \underline{\underline{2 \text{ V}}}$$

$$V_{c2} = V_{cc} - 0 \times R_c = \underline{\underline{5 \text{ V}}}$$



7.22



7.23

$$i_{E1} = \frac{I}{1 + e^{(V_{B2} - V_{B1})/V_T}} = 0.8 I$$

$$\rightarrow V_{B2} - V_{B1} = V_T \ln 0.25$$

$$= -34.6 \text{ mV}$$

Thus, $V_{B1} - V_{B2} = \underline{\underline{34.6 \text{ mV}}}$

7.24

$$(a) V_{CMmax} = V_{C1,2} = \underline{\underline{V_{CC} - \frac{I}{2} R_C}}$$

(b) If the current is steered to Q_1 , then

$$V_{C1} = V_{CC} - I R_C, \text{ a change of: } \underline{\underline{-\frac{I}{2} R_C}}$$

$$V_{C2} = V_{CC}, \text{ a change of } \underline{\underline{+\frac{I}{2} R_C}}$$

$$(c) V_{CMmax} = 3 = 5 - \frac{I}{2} R_C \\ \Rightarrow I R_C = \underline{\underline{4V}}$$

$$(d) \frac{I/2}{\beta+1} \leq 2 \mu A$$

$$\Rightarrow I \leq 4(\beta+1) \mu A$$

$$\text{Thus, } I = 4 \times 101 \mu A = 0.404 \text{ mA}$$

$$\text{Select } I = \underline{\underline{0.4 \text{ mA}}}$$

$$R_C = \frac{4V}{I} = \frac{4V}{0.4 \text{ mA}} = \underline{\underline{10 \text{ k}\Omega}}$$

7.25

$$i_{E1} = \frac{I}{1 + e^{-\frac{V_D}{V_T}}}, \quad V_D = V_{B1} - V_{B2}$$

$$\frac{\Delta i_{E1}}{I} \approx \frac{i_{E1} - I/2}{I} = \frac{i_{E1}}{I} - 0.5$$

Define normalized Gain

$$G_N \equiv \frac{\Delta i_{E1} / I}{V_D}$$

V_D (mV)	5	10	20	30	40
G_N	9.97	9.87	9.50	8.95	8.30

Observe that the gain stays relatively constant up to V_D nearly 20 mV. Then it decreases significantly with the increase in signal level. Whenever gain depends on signal level, nonlinear distortion occurs.

7.26

With:

$$V_{B1} - V_{B2} = 10 \text{ mV}$$

$$i_{E1} = \frac{I}{1 + e^{-10/25}} = 0.598 I$$

$$\text{Since } i_{E1} + i_{E2} = I$$

$$i_{E2} = 0.402 I$$

For a collector resistance R_C

$$\begin{aligned} V_O = V_{C1} - V_{C2} &= (V_{CC} - i_{E1} R_C) - (V_{CC} - i_{E2} R_C) \\ &= -(i_{E2} - i_{E1}) R_C \\ &= -\alpha (i_{E2} - i_{E1}) R_C \\ &\approx -0.196 I R_C \end{aligned}$$

Thus, for

$$V_O = 1V; \quad 0.196 I R_C = 1$$

$$I R_C = 5.102$$

Now $I = 2 \text{ mA}$, thus

$$R_C = \underline{\underline{2.5 \text{ k}\Omega}}$$

DC (bias) voltage at each collector

$$= V_{CC} - \frac{I}{2} R_C = 10 - 1 \times 2.5 = 7.5 \text{ V}$$

For a -1 V output swing, the minimum voltage at each collector is:

CONT.

$$7.5 - 0.5 = 7.0V$$

Thus, $V_{icm}|_{max} = \underline{7V}$

7.27

$$i_{E1} = \frac{I}{1 + e^{(V_{B2} - V_{B1})/V_T}}$$

$$i_{E2} = \frac{I}{1 + e^{(V_{B1} - V_{B2})/V_T}}$$

For $V_{B1} - V_{B2} = 5mV$, $V_T = 25mV$

$$\begin{aligned} i_{E1} &= 0.550I \\ i_{E2} &= 0.450I \end{aligned} \quad \left\{ \begin{array}{l} \text{Note that } i_{E1} + i_{E2} = I \\ \text{as should be the case.} \end{array} \right.$$

$\alpha \approx 1$, thus $i_{C1} = 0.55I$
 $i_{C2} = 0.45I$

$$\begin{aligned} V_o &= V_{C2} - V_{C1} \\ &= (V_{CC} - i_{C2}R_c) - (V_{CC} - i_{C1}R_c) \\ &= (i_{C1} - i_{C2})R_c \\ &= 0.10 I R_c \end{aligned}$$

Voltage gain $A_V = \frac{V_o}{V_{B1} - V_{B2}} = \frac{0.1 I R_c}{0.005} = \underline{20 I R_c \text{ V/V}}$

(b) Bias voltage at each collector is: $V_{CC} - \frac{I R_c}{2}$

For an output differential voltage of $0.1 I R_c$, each collector should be allowed to fall by $(0.05 I R_c)$ below its bias value, thus

$$\begin{aligned} V_{cmin} &= V_{CC} - 0.5 I R_c - 0.05 I R_c \\ &= V_{CC} - 0.55 I R_c \end{aligned}$$

Thus for operation in saturation with

$$V_{CB} = 0 \text{ (minimum)}$$

$$V_{icm}|_{max} = V_{cmin} = V_{CC} - 0.55 I R_c$$

$$\begin{aligned} &= V_{CC} - 0.55 \frac{A_V}{20} \\ &= \underline{V_{CC} - 0.0275 A_V} \end{aligned}$$

Obviously for a given V_{CC} , increasing A_V reduces the maximum allowable V_{icm}

A_V (V/V)	100	200	300	400
$V_{icm} _{max}$ (V)	$V_{CC} - 2.75$	$V_{CC} - 5.5$	$V_{CC} - 8.25$	$V_{CC} - 11$
$I R_c$ (V)	5	10	15	20
R_c (k Ω)	5	10	15	20

Example: For $V_{CC} = 10V$, a gain of 200 can be achieved using $R_c = 10k\Omega$. The corresponding maximum input common-mode voltage is 4.5V. If a gain of 300 is required, it can be achieved by increasing R_c to 15k Ω , however the maximum permitted input common-mode voltage then becomes 1.75V only!

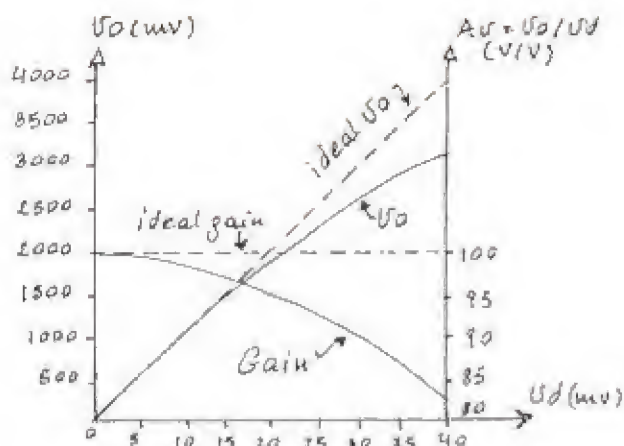
7.28

$$\begin{aligned} i_{C1} &= \alpha i_{E1} \approx i_{E1} = I / (1 + e^{-V_{od}/V_T}) \\ i_{C2} &= \alpha i_{E2} \approx i_{E2} = I / (1 + e^{V_{od}/V_T}) \\ V_o &= V_{C2} - V_{C1} = (V_{CC} - i_{C2}R_c) - (V_{CC} - i_{C1}R_c) \\ &= I R_c \left(\frac{1}{1 + e^{-V_{od}/V_T}} - \frac{1}{1 + e^{V_{od}/V_T}} \right) \end{aligned}$$

For $I R_c = 5V$:

$V_{od}(mV)$	5	10	15	20	25	30	35	40
$V_{oh}(mV)$	498	987	1457	1900	2311	2685	3022	3320
$\frac{V_o}{V_{od}}$ (V/V)	99.7	98.7	97.1	95.0	92.4	89.5	86.3	83.0

CONT.



7.29

$$I = 6 \text{ mA}$$

The current will divide between the two transistors in proportion to their emitter areas. Thus with no input,

$$I_{E1} = 1.5 I_{E2}$$

$$I_{E1} + I_{E2} = 2.5 I_{E2} = 6 \text{ mA}$$

$$I_{E2} = 2.4 \text{ mA}$$

$$I_{E1} = 3.6 \text{ mA}$$

For $\alpha \approx 1$

$$I_{C1} = 3.6 \text{ mA}$$

$$I_{C2} = 2.4 \text{ mA}$$

To equalize the collector currents we apply a difference signal $V_D = V_{B2} - V_{B1}$ whose value can be determined as follows:

$$I_{E1} = I_{SE1} e^{(V_{B1} - V_E)/V_T}$$

$$I_{E2} = I_{SE2} e^{(V_{B2} - V_E)/V_T}$$

where $I_{SE1}/I_{SE2} = 1.5$

Now, $I_{E1} = I_{E2}$ when

$$1 = 1.5 e^{(V_{B1} - V_{B2})/V_T}$$

$$V_D = V_{B2} - V_{B1} = V_T \ln 1.5 = \underline{\underline{10.1 \text{ mV}}}$$

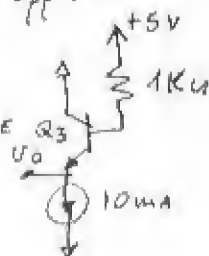
7.30

Refer to Fig. P7.30

(a) For V_I sufficiently low so that Q_1 is cut off:

$$V_{BE}|_{Q3} = 0.7 + V_T \ln \frac{10}{1} = 0.76 \text{ V}$$

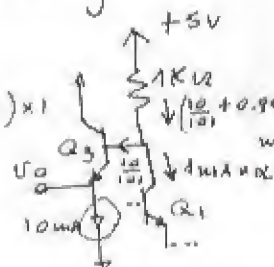
$$V_{OH} = V_O = 5 - \frac{10}{101} - V_{BE} = 5 - \frac{10}{101} - 0.76 = \underline{\underline{4.14 \text{ V}}}$$



(b) For V_I sufficiently high so that Q_1 is conducting all the current I :

$$V_{BE}|_{Q3} = 0.76 \text{ V}$$

$$V_{OL} = V_O = 5 - \left(\frac{10}{101} + 0.99 \right) \times 1 - 0.76 = \underline{\underline{3.15 \text{ V}}}$$



$$(c) I_{E1} = I / (1 + e^{(V_{B2} - V_{B1})/V_T}) = I / 100$$

$$e^{(3.64 - V_I)/V_T} = 99$$

$$V_I = 3.64 - V_T \ln 99 = \underline{\underline{3.525 \text{ V} = V_{IL}}}$$

$$(d) I_{E1} = 0.99 I = \frac{I}{1 + e^{(3.64 - V_{IH})/V_T}}$$

$$1 + e^{(3.64 - V_{IH})/V_T} = 1.01$$

$$V_{IH} = 3.64 + V_T \ln 100 = \underline{\underline{3.755 \text{ V}}}$$

$$(e) V_O$$

$$V_{OH} = 4.14$$

$$\frac{1}{2} (V_{OL} + V_{OH}) = 3.64$$

$$V_{OL} = 3.15$$

$$NML = 0.375 \text{ V}$$

$$V_{IL} = 3.525 \text{ V}$$

$$V_{IH} = 3.755 \text{ V}$$

$$\text{Midpoint: } (V_{IL} + V_{IH})/2 = 3.64 \text{ V}$$

CONT

Since the mid-point of the output voltage swing is equal to 3.64V, the output voltage swing is centred on the mid-point of the input range; an ideal choice for it equalizes the noise margins.

7.31

Each device is operating at a current of $150\mu A = 0.15mA$. Thus,

$$g_m = \frac{0.15mA}{25mV} = \frac{6mA}{V}$$

$$R_{id} = 2(\beta+1)r_e = 2r_{\pi} = 2 \times \frac{150}{4} = \underline{75K\Omega}$$

7.32

$$R_{id} > 10K\Omega; A_d = 200V/V;$$

$$\beta > 100; V_{CC} = 10V$$

$$R_{id} = 10^4 = 2r_{\pi} = 2 \times \frac{100}{g_m}$$

$$\Rightarrow g_m = 20mA/V$$

Thus each device is operating at 0.5mA and $I = \underline{1mA}$

$$\begin{aligned} \text{Voltage gain} &= g_m R_c \\ 200 &= 20 R_c \\ \Rightarrow R_c &= \underline{10K\Omega} \end{aligned}$$

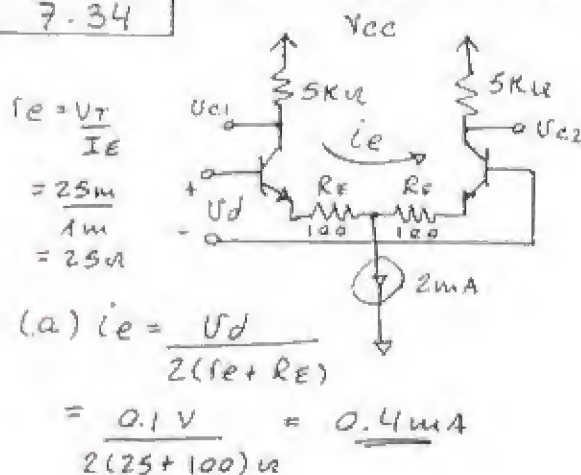
7.33

$$r_e = \frac{V_T}{I/2} = \frac{25mV}{50\mu A} = \underline{500\Omega}$$

$$\begin{aligned} \text{Half-circuit gain} &= \frac{\alpha R_c}{r_e} \approx \frac{R_c}{r_e} \\ &= \frac{10K}{500} = \underline{20V/V} \end{aligned}$$

At one collector we expect a signal of (+100mV) and at the other a signal of (-100mV)

7.34



$$\begin{aligned} (b) \quad i_{E1} &= 1 + 0.4 = \underline{1.4\mu A} \\ i_{E2} &= 1 - 0.4 = \underline{0.6\mu A} \end{aligned}$$

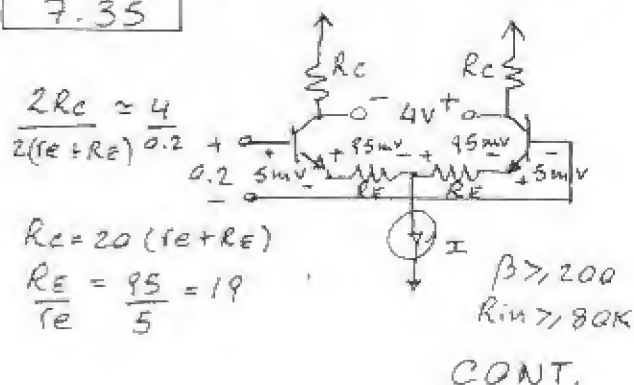
$$(c) \quad V_{c1} = -i_{E1}R_c \approx -0.4 \times 5 = \underline{-2V}$$

$$V_{c2} = \underline{+2V}$$

$$(d) \quad V_{od} = 4V$$

$$A_d = V_{od}/V_{id} = \frac{4}{0.1} = \underline{40V/V}$$

7.35



$$R_{in} = 2(\beta+1)(r_e + R_E)$$

$$= 2 \times 201 \times 201e = 80K\Omega$$

$$\Rightarrow r_e \approx \frac{80000}{8000} = 10\Omega$$

Thus each device is operating at a current of $\frac{25mV}{10\Omega} = 2.5mA$

$$\Rightarrow I = \underline{5mA}$$

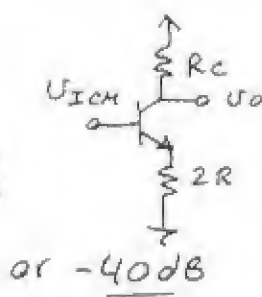
$$R_E = 19 \times 10 = 190\Omega$$

$$R_C = 20 \times 200 = \underline{4K\Omega}$$

7.36

$$\frac{2M\Omega}{U_{ICM}} \approx \frac{R_C}{2R} = \frac{20K\Omega}{2M\Omega}$$

$$= \underline{0.01 V/V}$$



or $\underline{-40dB}$

7.37

Refer to Fig. P7.37

$$\frac{U_O}{U_i} = \frac{\alpha \times 20K\Omega}{(2r_e + 2 \times 200)\Omega}$$

$$\text{Where } r_e = \frac{V_T}{I_E} = \frac{0.05V}{0.5/2} = 100\Omega$$

$$\frac{U_O}{U_i} \approx \frac{20000}{500} = \underline{33.3V/V}$$

$$R_i = (\beta+1)(2r_e + 2 \times 200)$$

$$= 101 \times 2 \times 300 \approx \underline{60K\Omega}$$

7.38

Refer to Fig P.7.38

Each transistor is operating at $I_E = 1mA$, thus

$$r_e = 25\Omega \text{ and } r_{\pi} = 101 \times 25 = 2525\Omega$$

$$\frac{U_O}{U_i} = \frac{\alpha \times 7.5K\Omega}{(2r_e + 200)\Omega} \approx \frac{7500}{250} = \underline{30}$$

$$R_i = (\beta+1)(r_e + 200 + r_e) \approx \underline{25K\Omega}$$

7.39

Refer to Fig P.7.39

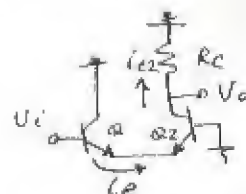
(a) As a differential amplifier the gain is given by

$$\frac{U_O}{U_i} = \frac{\alpha R_C}{2r_e} \quad (1)$$

(b) Transistor Q_1 can be considered as a common-collector stage. It is biased at $I/2$ and has a resistance r_{e2} in its emitter, thus.

$$i_e = \frac{U_i}{r_{e1} + r_{e2}}$$

$$= \frac{U_i}{2r_e} \quad (2)$$



Now, Q_2 is connected in the common-base configuration. It has an input signal current i_e . Thus its collector signal current (in the direction indicated) will be $i_{c2} = \alpha i_e \quad (3)$

The output voltage will be

$$U_O = i_{c2} R_C \quad (4)$$

Combining equations (2) (3) and (4) provides:

CONT.

$\frac{V_o}{V_i} = \frac{\alpha R_c}{2r_e}$, which is identical to the result found above in part (a)

7.40

(a) $V_E = -0.7V$

Thus, $I = \frac{-0.7 - (-5)}{4.3} = 1mA$ $r_e = 50\Omega$

$A_d = \frac{V_o}{V_d} = \frac{\alpha \times 2}{2r_e} \approx \frac{2000}{2 \times 50} = \underline{\underline{20 V/V}}$

(b) $A_{cm} = \frac{\alpha R_c}{8.6 + r_e}$
 $= \frac{2}{8.65} = \underline{\underline{0.23 V/V}}$



(c) CMRR
 $= 20 \log \left| \frac{A_d}{A_{cm}} \right| = 20 \log \frac{20}{0.23}$
 $= \underline{\underline{38.8 dB}}$

(d) $V_d = 2 \times 0.005 \sin(2\pi \times 1000t)$

$V_{icm} = 0.1 \sin(2\pi \times 60t)$

Thus, $V_o = A_d \cdot V_d + A_{cm} \cdot V_{icm}$
 $= 20 \times 0.01 \sin 2\pi \times 1000t$
 $+ 0.23 \times 0.1 \sin(2\pi \times 60t)$
 $= \underline{\underline{0.2 \sin 2\pi \times 1000t + 0.023 \sin 2\pi \times 60t}}$

7.41

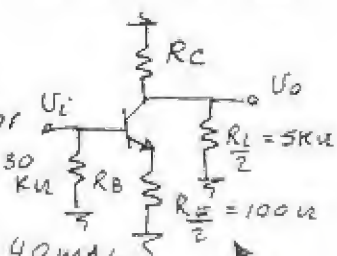
Each transistor

is biased at 1mA. Thus,

$r_e = 25\Omega$, $g_m = 40mA/V$

$r_o = 100/\text{I} = 100K\Omega$

The differential half-circuit is



$A_d = \frac{V_o}{V_i} = \alpha \frac{R_c \parallel (R_L/2)}{r_e + R_E/2}$
 $\approx \frac{10/15}{0.025 + 0.100} = \underline{\underline{26.7 V/V}}$

$R_{id} = 2[R_B \parallel (\beta+1)(r_e + R_E/2)]$
 $= 2[30 \parallel 101(0.025 + 0.100)]$
 $= \underline{\underline{17.8 K\Omega}}$

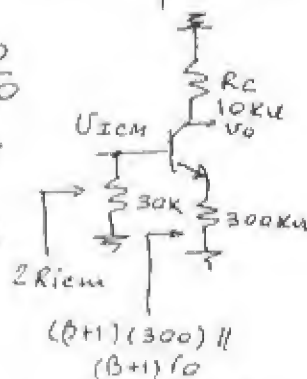
The common-mode half-circuit

$A_{cm} = \frac{V_o}{V_{icm}} \approx \frac{10}{300}$
 $= \frac{1}{30} = \underline{\underline{0.033 V/V}}$

$2R_{icm} = 30K \parallel 7.5K\Omega$
 $= 30K\Omega$

$R_{icm} = \underline{\underline{15 K\Omega}}$

Without the R_B resistors $R_{icm} = 3.75 K\Omega$



7.42

(a) $A_d \big|_{\text{single-ended output}} = \frac{\alpha (R_c \parallel r_o)}{2r_e}$

where $r_e = \frac{0.025V}{0.25mA} = 100\Omega$

$r_o = \frac{200V}{0.25mA} = 800K\Omega$

$A_d \big|_{\text{single-ended}} \approx \frac{20}{2 \times 0.1} = \underline{\underline{100 V/V}}$

(b) $A_d \big|_{\text{diff}} = 2 \times A_d \big|_{\text{single-ended}}$
 $= \underline{\underline{200 V/V}}$

(c) $R_{id} = 2r_{\pi} = 2 \times 201 \times 100$
 $= \underline{\underline{40.2 K\Omega}}$

CONT.

$$(d) A_{cm} \Big|_{\text{single-ended output}} = \frac{R_c}{2R}$$

$$= \frac{20}{2000} = 0.01 \text{ V/V}$$

$$(e) A_{cm} \Big|_{\text{diff out}} = 0$$

7.43

The output resistance of the current source (R) = $r_o = \frac{V_A}{I_{CQ}}$

$$= \frac{200}{0.1} = 2 \text{ M}\Omega$$

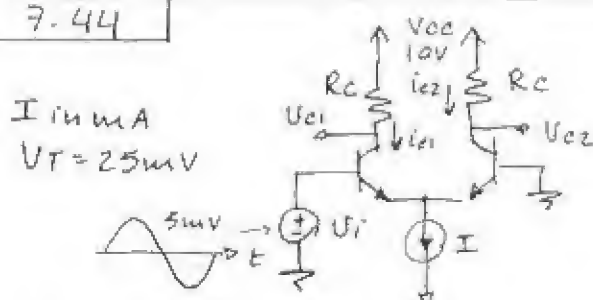
r_o for each transistor is the pair = $200/0.05 = 4 \text{ M}\Omega$

Thus,

$$R_{icm} = \frac{(\beta+1)r_o \parallel (\beta+1)R}{2}$$

$$= \frac{51 \times 4 \parallel 51 \times 2}{2} = 51 \text{ M}\Omega$$

7.44



$$i_{c1} = \frac{I}{2} + \left(\frac{I/2}{V_T} \right) \left(\frac{5}{2} \right) \sin \omega t$$

$$i_{c2} = \frac{I}{2} - \left(\frac{I/2}{V_T} \right) \left(\frac{5}{2} \right) \sin \omega t$$

$$u_{c1} = V_{cc} - \frac{I}{2} R_c - \frac{I/2}{V_T} R_c \frac{5}{2} \sin \omega t$$

$$u_{c2} = V_{cc} - \frac{I}{2} R_c - \frac{I/2}{V_T} R_c \frac{5}{2} \sin \omega t$$

$$u_{c1}, u_{c2} \geq 0$$

$$\Rightarrow 10 - 5I - 0.5I = 0$$

$$I = 1.8 \text{ mA}$$

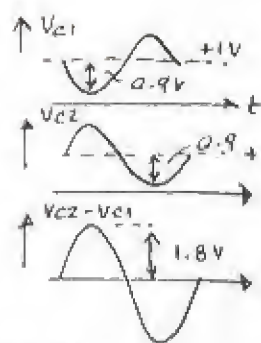
$$V_{c1} = V_{c2} = 1 \text{ V}$$

$$A_d = \frac{20 \text{ K}\Omega}{2 r_e}, \text{ where}$$

$$r_e = \frac{25}{0.9} = 27.8 \Omega$$

$$\text{Thus, } A_d = 360 \text{ V/V}$$

$$u_{c2} - u_{c1} = 1.8 \sin \omega t, \text{ V}$$



7.45

At $I_C = 1 \text{ mA}$, $r_e = 25 \Omega$

$$R_{id} = (\beta+1) 2r_e = 5.05 \text{ K}\Omega < 10$$

\Rightarrow need emitter resistors

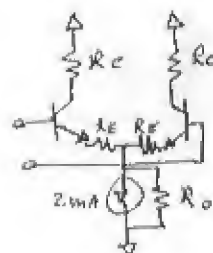
In this case:

$$R_{id} = (\beta+1) (2r_e + 2R_E) = 10 \text{ K}$$

$$\text{Thus, } R_E = 25 \Omega$$

$$A_d = 100 = \frac{R_c}{2(R_E + r_e)}$$

$$\Rightarrow R_c = 10 \text{ K}$$



$$A_{cm} = 0.1 > \frac{R_c}{2R_o + R_E + r_e}$$

$$\Rightarrow R_o > 50 \text{ K}\Omega$$

For ± 2 swing $u_{c1} = u_{c2} = V_{cc} - \frac{I}{2} R_c = 2$

$$\Rightarrow V_{cc} = 2 + 10^3 \times 10^4 = 12 \text{ V}$$

Choose $V_{cc} = \pm 15 \text{ V}$ although 12V is OK.

$$2 R_{icm} = (\beta+1) (2R_o + R_E + r_e)$$

$$\Rightarrow R_{icm} = 5 \text{ M}\Omega$$

7.46

Taken single-endedly

$$A_{em_s} = \frac{\alpha R_c}{2R_o}$$

Let collector resistors be R_c & $R_c + \Delta R_c$, then

$$\begin{aligned} A_{em} &= \frac{\alpha}{2R_o} (R_c + \Delta R_c - R_c) \\ &= \alpha \frac{\Delta R_c}{2R_o} \end{aligned}$$

Which can be written as

$$A_{em_d} = \frac{\alpha R_c}{2R_o} \cdot \frac{\Delta R_c}{R_c} = A_{em_s} \frac{\Delta R_c}{R_c}$$

$$CHRR = \frac{A_d}{A_{em_d}} = \frac{2 \cdot A_s}{A_{em_s} \frac{\Delta R_c}{R_c}}$$

$$= \frac{A_s}{A_{em_s}} \cdot \frac{2}{\frac{\Delta R_c}{R_c}}$$

$$\text{Thus, } 20 \log \frac{2}{\frac{\Delta R_c}{R_c}} = 40 \text{ dB}$$

$$\Rightarrow \Delta R_c / R_c = \underline{\underline{2\%}}$$

7.47

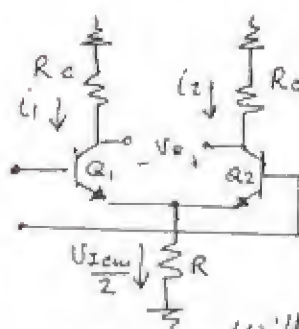
The bias current will split between the two transistors according to their area ratio. Thus the large-area device will carry twice the current of the other device.

That is, the bias currents will be $2I/3$ and $I/3$.

Now with V_{icm} applied, the CM signal current will

$$\rightarrow V_{icm}/R$$

split between Q_1 and Q_2 in the same ratio. This is



because their r_e values will be related in the same way. Thus, if Q_1 is the large device r_{e1} will be half the

value of r_{e2} .

The result will be that

$$i_1 = \frac{2}{3} \frac{V_{icm}}{R} \text{ and } i_2 = \frac{1}{3} \frac{V_{icm}}{R}$$

Thus the differential output voltage V_o will be

$$\begin{aligned} V_o &= i_1 R_c - (-i_2 R_c) = (i_1 - i_2) R_c \\ &= \frac{1}{3} \frac{V_{icm}}{R} \cdot R_c \end{aligned}$$

$$A_{em} = \frac{1}{3} \frac{R_c}{R} = \frac{1}{3} \times \frac{12}{1000} = \underline{\underline{0.004 \text{ V/V}}}$$

7.48

For $I = 200 \mu A$:

$$\begin{aligned} g_m &= \sqrt{2 K_n' W/L I_D} = \sqrt{2 \times 4 \times 0.1} \\ &= 0.89 \text{ mA/V} \end{aligned}$$

$$R_D = 10 \text{ k}\Omega$$

$$\text{Thus, } A_d = g_m R_D = 10 \times 0.89 = \underline{\underline{8.9 \text{ V/V}}}$$

$$V_{os} = \frac{(V_{GS} - V_t)}{2} \cdot \frac{\Delta R_D}{R_D}$$

$$\text{where } \frac{\Delta R_D}{R_D} = 0.02 \text{ (worst case)}$$

$$\begin{aligned} \text{and } V_{GS} - V_t &= \sqrt{\frac{2 I_D}{K_n' W/L}} = \sqrt{\frac{2 \times 0.1}{4}} \\ &= \underline{\underline{0.223 \text{ V}}} \end{aligned}$$

CONT.

$$\text{Thus, } V_{os} = \frac{1}{2} \times 0.223 \times 0.02$$

$$= \underline{2.23 \text{ mV}}$$

For $I = 400 \mu\text{A}$:

$$g_m = \sqrt{2 \times 4 \times 0.2} = 1.265 \text{ mA/V}$$

$$A_d = \underline{12.65 \text{ V/V}}$$

$$V_{ov} = V_{GS} - V_t = 0.316 \text{ V}$$

$$V_{os} = \frac{1}{2} \times 0.316 \times 0.02 = \underline{3.16 \text{ mV}}$$

Thus both A_d and V_{os} increase by the same ratio since both are proportional to \sqrt{I}

To find the required mismatch, ΔR_D that can correct for V_{os}

$$13.11 \text{ mV} = \frac{V_{ov}}{2} \cdot \frac{\Delta R_D}{R_D}$$

$$\Rightarrow \frac{\Delta R_D}{R_D} = \frac{2 \times 13.11 \text{ mV}}{0.3 \text{ V}}$$

$$= 0.087 \text{ or } \underline{8.7\%}$$

If ΔV_t is reduced by a factor of 10 to 1 mV , V_{os} reduces to:

$$\sqrt{6^2 + 6^2 + 1^2} = 8.54 \text{ mV}$$

$$\text{And } \frac{\Delta R_D}{R_D} = \frac{2 \times 8.54 \text{ mV}}{0.3 \text{ V}} = \underline{5.6}$$

7.49

Worst cases: $\Delta V_t = 10 \text{ mV}$

$$\frac{\Delta R_D}{R_D} = 0.04; \frac{\Delta(W/L)}{(W/L)}$$

$$V_{os1} (\text{due to } \Delta R_D) = \frac{V_{ov}}{2} \frac{\Delta R_D}{R_D} = \frac{0.3 \times 0.04}{2}$$

$$= 6 \text{ mV}$$

$$V_{os2} (\text{due to } \Delta W/L) = \frac{V_{ov}}{2} \frac{\Delta W/L}{W/L} = \frac{0.3 \times 0.04}{2}$$

$$= 6 \text{ mV}$$

$$V_{os3} (\text{due to } \Delta V_t) = \Delta V_t = \underline{10 \text{ mV}}$$

Since these offsets are not correlated

$$V_{os} = \sqrt{V_{os1}^2 + V_{os2}^2 + V_{os3}^2}$$

$$V_{os} = \sqrt{6^2 + 6^2 + 10^2} = \underline{13.11 \text{ mV}}$$

The major contribution is due to the threshold mismatch ΔV_t .

7.50

$$V_{ov} = \sqrt{\frac{I}{K_n' W/L}} = \sqrt{\frac{100}{100 \times 20}} = 0.223$$

Using Egn. (7.112) we obtain V_{os} due to $\Delta R_D/R_D$ as:

$$V_{os} = \frac{V_{ov}}{2} \frac{\Delta R_D}{R_D} = \frac{0.223 \times 0.02}{2}$$

$$= 5.57 \text{ mV}$$

From Egn. (7.117), V_{os} due to $\Delta(W/L)/(W/L)$ is:

$$V_{os} = \left(\frac{V_{ov}}{2} \right) \frac{\Delta W/L}{W/L} = \frac{0.223 \times 0.02}{2}$$

$$= 5.57 \text{ mV}$$

The offset arising from ΔV_t (Egn. (7.120)):

$$V_{os} = \Delta V_t = \underline{5 \text{ mV}}$$

Worst case offset is:

$$5.57 + 5.57 + 5 = 16.15 \text{ mV}$$

Applying the root-sum-of-squares (Eg. (7.121))

$$V_{os} = \sqrt{2(5.57 \text{ mV})^2 + 5^2} = \underline{9.33 \text{ mV}}$$

7.51

$$\Delta V_c = \Delta R_c \cdot \frac{I}{2}$$

$$A_d = \frac{R_c}{r_e} = \frac{R_c}{V_T / \frac{I}{2}} = \frac{I R_c}{2 V_T}$$

$$\Rightarrow V_{os} = \frac{\Delta V_c}{A_d} = \frac{\Delta R_c}{R_c} \cdot V_T$$

$$= 0.1 \times 25 = \underline{\underline{2.5 \text{ mV}}}$$

7.52

Eq (7.130) $V_{os} = V_T \cdot \frac{\Delta I_S}{I_S}$

$$= 25 \times 0.1 = \underline{\underline{2.5 \text{ mV}}}$$

7.53

$$\Delta V_c = \Delta R_c \frac{I}{2}$$

$$A_d = \frac{R_c}{r_e + R_e} = \frac{R_c}{\frac{2 V_T + R_e I}{I}} = \frac{I R_c}{2 V_T + I R_e}$$

$$V_{os} = \frac{\Delta V_c}{A_d} = \frac{\Delta R_c}{R_c} \left(V_T + \frac{I R_e}{2} \right)$$

7.54

$$\Delta V_c = \alpha_1 \frac{I}{2} R_c - \alpha_2 \frac{I}{2} R_c$$

$$= \frac{I}{2} R_c (\alpha_1 - \alpha_2)$$

$$= \frac{I}{2} R_c \left(\frac{\beta_1}{\beta_1 + 1} - \frac{\beta_2}{\beta_2 + 1} \right)$$

For $\beta_1, \beta_2 \gg 1$

$$\Delta V_c = \frac{I}{2} R_c \cdot \frac{\beta_1 - \beta_2}{\beta_1 \beta_2}$$

$$= \frac{I}{2} R_c \left(\frac{1}{\beta_2} - \frac{1}{\beta_1} \right)$$

$$A_d = \frac{R_c}{r_e} = \frac{I R_c}{2 V_T}$$

$$V_{os} = \frac{\Delta V_c}{A_d} = V_T \left(\frac{1}{\beta_2} - \frac{1}{\beta_1} \right) \quad \text{Q.E.D.}$$

For $\beta_1 = 100$ and $\beta_2 = 200$

$$V_{os} = 25 \left(\frac{1}{200} - \frac{1}{100} \right)$$

$$= \underline{\underline{-125 \mu\text{V}}}$$

7.55

Since the two transistors are matched except for their V_A value, we can express the collector currents when the input terminals are grounded as,

$$I_{C1} = I_C \left(1 + \frac{V_{CE}}{V_{A1}} \right)$$

$$I_{C2} = I_C \left(1 + \frac{V_{CE}}{V_{A2}} \right)$$

where I_C can be determined from

$$I_{C1} + I_{C2} = I$$

$$\Rightarrow I_C = \frac{I}{2 + \frac{V_{CE}}{V_{A1}} + \frac{V_{CE}}{V_{A2}}}$$

Note that for $V_{CE} \ll V_{A1}, V_{A2}$, $I_C \approx \frac{I}{2}$. Thus, the differential gain A_d can still be written as

$$A_d \approx \frac{R_c}{r_e} = \frac{I R_c}{2 V_T}$$

The offset voltage at the output can be found from

$$\Delta V_c = V_{C2} - V_{C1} = (I_{C1} - I_{C2}) R_c$$

CONT.

$$= I_C R_C \left(\frac{V_{CE}}{V_{A1}} - \frac{V_{CE}}{V_{A2}} \right)$$

$$\approx \frac{I}{2} R_C \left(\frac{V_{CE}}{V_{A1}} - \frac{V_{CE}}{V_{A2}} \right)$$

Thus, $V_{os} = \frac{\Delta V_C}{A_d}$

$$V_{os} = V_T \left(\frac{V_{CE}}{V_{A1}} - \frac{V_{CE}}{V_{A2}} \right)$$

For $V_{CE} = 10V$, $V_{A1} = 100V$ and $V_{A2} = 300V$

$$V_{os} = 25 \left(\frac{10}{100} - \frac{10}{300} \right)$$

$$= \underline{\underline{1.7mV}}$$

7.56

Equating the incremental

changes in voltage from ground to emitter on both sides of the pair (and neglecting second-order terms i.e. $\Delta I \Delta$ terms):

$$\frac{I}{2(\beta+1)} \cdot \frac{\Delta R_s}{2} - \frac{\Delta I}{2(\beta+1)} \cdot R_s - \frac{\Delta I}{2} \cdot r_e$$

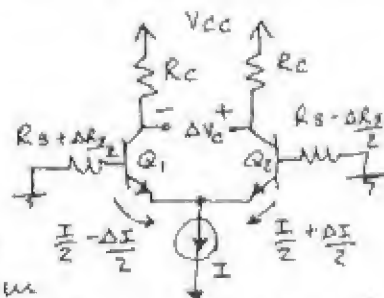
$$\approx -\frac{I}{2(\beta+1)} \frac{\Delta R_s}{2} + \frac{\Delta I}{2(\beta+1)} R_s + \frac{\Delta I}{2} r_e$$

$$\Delta I \left[r_e + \frac{R_s}{\beta+1} \right] = \frac{I}{2(\beta+1)} \cdot \Delta R_s$$

$$\Delta I = \frac{I}{2(\beta+1)} \cdot \frac{\Delta R_s}{r_e + \frac{R_s}{\beta+1}}$$

$$\Delta V_C = -\Delta I \cdot R_C$$

$$= -\frac{I R_C \Delta R_s}{2(\beta+1)} \cdot \frac{1}{r_e + R_s/(\beta+1)}$$



$$A_d = R_C / r_e$$

Thus, $V_{os} = \Delta V_C / A_d$

$$= -\frac{I \Delta R_s}{2(\beta+1)} \cdot \frac{r_e}{r_e + \frac{R_s}{\beta+1}}$$

For $\frac{R_s}{\beta+1} \ll r_e$ and $\beta \gg 1$,

$$|V_{os}| \approx \frac{I}{2\beta} (\Delta R_s) \quad \text{Q.E.D.}$$

7.57

Refer to Fig. P7.57.

(a) $R_{C1} = 5 \times 1.05 = 5.25K\Omega$

$R_{C2} = 5 \times 0.95 = 4.75K\Omega$

Perfect offset nulling will be achieved when x is such that

$$R_{C1} + (x \times 1K) = R_{C2} + (1-x) \times 1K$$

$$\Rightarrow 5.25 + x = 4.75 + 1 - x$$

$$\Rightarrow x = \underline{\underline{0.25}}$$

(b) $I_{C1} = 1.05mA$

$I_{C2} = 0.95mA$

Offset nulling is achieved when x is such that

$$1.05(x+5) = 0.95(1-x+5)$$

$$x = \underline{\underline{0.225}}$$

7.58

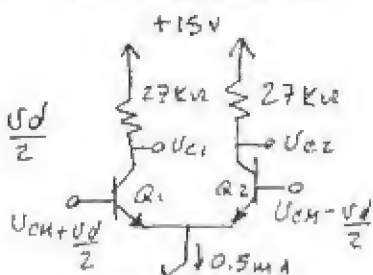
$$I_{Bmax} = \frac{I/2}{\beta_{min}+1} = \frac{300}{80+1} = \underline{\underline{3.7\mu A}}$$

$$I_{Bmin} = \frac{I/2}{\beta_{max}+1} = \frac{300}{200+1} = \underline{\underline{1.5\mu A}}$$

$$I_{os} = I_{Bmax} - I_{Bmin} = \underline{\underline{2.2\mu A}}$$

7.59

$$V_{C1} \geq V_{CE} + \frac{V_d}{2}$$



$$15 - 0.25 \times 27 - g_m \frac{V_d}{2} \times 27 \geq V_{CE} + \frac{V_d}{2}$$

$$\text{Thus } V_{CE}|_{\max} = 15 - 0.25 \times 27 - 100 \times 0.01 \times 27 - 0.01 = +5.54 \text{ V}$$

To find $V_{CE}|_{\min}$ we observe that to keep the current-source transistor in the active region, the voltage at its collector should exceed the collector-emitter saturation voltage (0.2-0.3V). Thus, $V_{E\min} = -4.7\text{V}$ and correspondingly $V_{CE\min} = -4\text{V}$

7.60

$$I_{E1} = \frac{2}{3}I \text{ and } I_{E2} = \frac{1}{3}I$$

(Q_1 twice the area of Q_2)

$$\Delta V_c = V_{C2} - V_{C1} = \frac{1}{3} I R_c$$

Nominally,

$$A_d = \frac{R_c}{r_e} = \frac{I R_c}{2V_T}$$

$$V_{OS} = \frac{\Delta V_c}{A_d} = \frac{2}{3} V_T = 16.7 \text{ mV}$$

Thus, small-signal analysis predicts that a 16.7 mV DC

voltage applied as $V_{B2} - V_{B1} = 16.7\text{V}$ would restore the current balance in the pair and reduce ΔV_c to zero.

Using large-signal analysis:

$$I_{E1} = I_{S1} \cdot e^{\frac{V_{B1} - V_E}{V_T}}$$

$$I_{E2} = I_{S2} \cdot e^{\frac{V_{B2} - V_E}{V_T}}$$

Thus,

$$\frac{I_{E1}}{I_{E2}} = \frac{I_{S1}}{I_{S2}} \cdot e^{\frac{V_{B1} - V_{B2}}{V_T}}$$

To restore balance, $I_{E1} = I_{E2}$, thus

$$1 = 2 e^{\frac{V_{B1} - V_{B2}}{V_T}}$$

$$\Rightarrow V_{B1} - V_{B2} = -V_T \ln 2$$

$$V_{B2} - V_{B1} = 17.3 \text{ mV}$$

Nominally

$$I_B = \frac{I/2}{\beta + 1} \approx \frac{100}{2 \times 100} = 0.5 \mu\text{A}$$

But with the imbalance,

$$I_{B1} \approx \frac{2I/3}{\beta} = \frac{2 \times 100}{300} = 0.67 \mu\text{A}$$

$$I_{B2} = \frac{I/3}{\beta} = \frac{100}{300} = 0.33 \mu\text{A}$$

$$I_B = \frac{I_{B1} + I_{B2}}{2} = 0.5 \mu\text{A}$$

$$I_{OS} = |I_{B1} - I_{B2}| = 0.34 \mu\text{A}$$

7.61

$$R_c = 20 \text{ k}\Omega ; A_d = 90 \text{ V/V}$$

$$V_{OS} = \pm 3 \text{ mV}$$

Worst case $|V_{OS}|$ is 3 mV

$$|V_{OS}| = V_T \left(\frac{\Delta R_c}{R_c} \right) \quad |V_{OS}| = 3 \text{ mV}$$

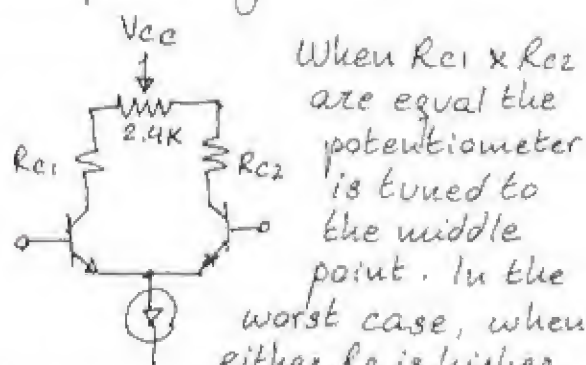
$$\Rightarrow \frac{3 \text{ mV} \times 20 \text{ k}\Omega}{25 \text{ mV}} = 2.4 \text{ k}\Omega, \Delta R_c = 2.4 \text{ k}\Omega$$

CONT.

This is the maximum mismatch that occurs in R_c .

Thus, if the lowest collector resistor is adjusted from $R_{cmin} + \Delta R$ with ΔR varying between zero and $2.4k\Omega$, then the offset would be eliminated.

This can be achieved with the following circuit:



When $R_{c1} \times R_{c2}$ are equal the potentiometer is tuned to the middle point. In the worst case, when either R_c is higher by $2.4k\Omega$, the potentiometer is adjusted to one extreme such as to increase the lowest R_c by $2.4k\Omega$. In all other cases when ΔR_c is distributed between R_{c1} and R_{c2} the potentiometer is adjusted as in Problem 7.57 above.

7.62

For each transistor $I_D = I/2$.
From Egn. (7.147): $r_{o2} = r_{o4} = r_o$
 $A_d = \frac{1}{2} g_{m1} r_o$

but $g_m = \frac{2I_D}{V_{ov}}$ and $r_o = \frac{V_A}{I_D}$
 $\Rightarrow A_d = \frac{1}{2} \left(\frac{2I_D}{V_{ov}} \right) \frac{V_A}{I_D} = \frac{V_A}{V_{ov}}$
 $\rightarrow 80 V/V = 20 V/V_{ov}$

$$\rightarrow V_{ov} = 20/80 = 0.25V$$

Finally,

$$I = 2I_D = \frac{K'_N W}{L} V_{ov}^2$$

$$= 3.2 \frac{mA}{V^2} (0.25V)^2 = \underline{\underline{0.2}}$$

7.63

For all transistors $I_D = I/2$ and all r_o 's are equal.

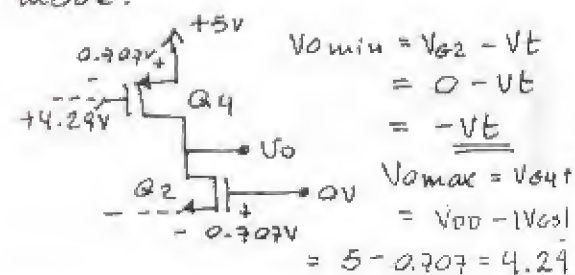
$$V_{ov} = \sqrt{\frac{2I_D}{K'_N W/L}} = \sqrt{\frac{100\mu A}{0.2mA/V^2}} = 0.7$$

$$V_{ov200} = \sqrt{\frac{400\mu A}{0.2mA/V^2}} = 1.414V$$

(a) For $I = 100\mu A$:

Range of the differential mode is $-\sqrt{2} V_{ov} \leq V_{id} \leq \sqrt{2} V_{ov}$ (as in Egn. (7.10))

But the range of V_o is limited by the requirement of keeping the transistors in saturation mode.



$$g_m = \frac{2I_D}{V_{ov}} \rightarrow g_{m1} = g_{m2} = \frac{100\mu A}{0.707V}$$

$$= 0.1414mA/V$$

$$r_o = \frac{V_A}{I_D} \Rightarrow r_{o2} = r_{o4} = \frac{20}{50\mu A} = 400k\Omega$$

$$R_o = r_{o2} || r_{o4} = \frac{1}{2} \times 400k\Omega = 200k\Omega$$

$$A_d = \frac{1}{2} g_{m1} r_o = \frac{1}{2} \times (0.1414mA/V) (400k\Omega)$$

CONT

$$A_d = \underline{\underline{28.28 \text{ V/V}}}$$

(b) For $I = 400 \mu\text{A}$:
Linear range of V_O

$$V_{O\min} = -V_E //$$

$$V_{O\max} = (5V - V_{GS}) + |V_E|$$

$$= \underline{\underline{5 - 1 = 4V}}$$

$$g_m = \frac{2 \times 200 \mu\text{A}}{1.414} = \underline{\underline{0.28 \text{ mA/V}}}$$

$$r_o = 20 / (400 / 2) = \underline{\underline{100 \text{ k}\Omega}}$$

$$R_o = 1/2 \cdot 100 \text{ k}\Omega = \underline{\underline{50 \text{ k}\Omega}}$$

$$A_d = \frac{1}{2} (0.28 \text{ mA/V} \times 100 \text{ k}\Omega) = \underline{\underline{14 \text{ V/V}}}$$

7.64

Recall from Eqn. (7.155)

$$CMRR = (g_m r_o) (g_m r_{ss})$$

(a) For a simple current mirror

$$r_{ss} = r_{o_s} \Rightarrow (\text{for } I_D = I/2)$$

$$CMRR = (g_m r_o) (g_m r_{o_s})$$

$$= \left(\frac{2I_D}{V_{OV}} \cdot \frac{V_A}{I_D} \right) \cdot \left(\frac{2I_D}{V_{OV}} \cdot \frac{V_A}{2I_D} \right)$$

$$= 2 \cdot \frac{V_A}{V_{OV}} \cdot \frac{V_A}{V_{OV}}$$

$$= 2 \left(\frac{V_A}{V_{OV}} \right)^2 \quad \text{Q.E.D.}$$

(b) for the modified Wilson current source of Fig. P7.64

$$r_{ss} \approx g_{m7} \cdot r_{o7} \cdot r_{o5}$$

$$\Rightarrow CMRR = (g_{m7} r_{o7}) (g_{m7} \cdot g_{m5} r_{o7} r_{o5})$$

For $Q_{5,6,7,8}$:

$$V_{OV3} = \sqrt{\frac{2I}{K'W/L}}$$

while for $Q_{1,2,3,4}$:

$$V_{OV} = \sqrt{\frac{I}{K'W/L}}$$

$$\Rightarrow V_{OV3} = \sqrt{2} V_{OV}$$

Thus, (for $I = 2I_D$)

$$CMRR = \frac{I}{V_{OV}} \cdot \frac{V_A}{(I/2)} \cdot \frac{I}{V_{OV}} \cdot \frac{2I}{\sqrt{2} V_{OV}} \cdot \frac{V_A}{I} \cdot \frac{V_A}{I}$$

$$= \frac{4 V_A^3}{\sqrt{2} V_{OV}^3} = \underline{\underline{2 \cdot \sqrt{2} \frac{V_A^3}{V_{OV}^3}}}$$

For $K'W/L = 10 \text{ mA/V}^2$
 $I = 1 \text{ mA}$

$$|V_A| = 10 \text{ V}$$

$$V_{OV} = \sqrt{\frac{1 \text{ mA}}{10 \text{ mA/V}^2}} = 0.316 \text{ V}$$

\Rightarrow For the simple current mirror case:

$$CMRR = 2 \left(\frac{10}{0.316} \right)^2 = 2000$$

$$\rightarrow \underline{\underline{66 \text{ dB}}}$$

For the Wilson source:

$$CMRR = 2 \sqrt{2} \frac{(10)^3}{(0.316)^3} = 89442$$

$$\rightarrow \underline{\underline{99 \text{ dB}}}$$

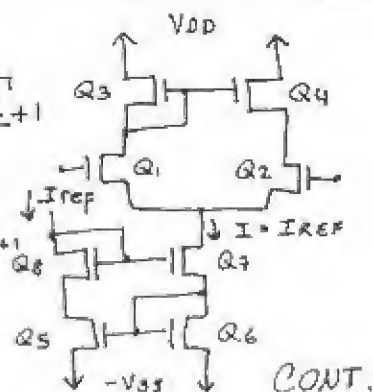
7.65

$$V_{GS1-4} = \sqrt{\frac{50 \mu\text{A} \cdot 2}{800 \mu\text{A}}} + 1$$

$$= 1.35 \text{ V}$$

$$V_{GS5-8} = \sqrt{\frac{2 \times 100 \mu\text{A}}{800 \mu\text{A}}} + 1$$

$$= 1.5 \text{ V}$$



For $V_{D3} = V_{G3}$
 $-V_{G3} + 2V_{G3_{5-8}} + 2V_{G3_{1-4}} = V_{DD}$

Thus,
 $V_{DD} + V_{G3} = 2(1.5) + 2(1.35)$
 $= \underline{\underline{5.7V}}$

$A_d = G_m R_o = 2 \times 1600 = \underline{\underline{3200 V/V}}$

With a subsequent stage having a $100k\Omega$ input resistance,

$A_d = G_m (R_o \parallel 100k\Omega)$
 $= \underline{\underline{188.2 V/V}}$

7.66

(b)

$R_{o4} = (g_{m4} r_{o4}) r_{o2}$
 $= g_{m4} r_{o2}^2$

$R_{o6} = (g_{m6} r_{o6}) r_{o8}$
 $= g_{m6} r_{o2}^2$

$A_d = g_m (R_{o4} \parallel R_{o6})$
 $= g_m \cdot \frac{1}{2} g_m^* r_{o2}^2$

$g_m = \frac{2I_D}{V_{ov}} \quad r_{o2} = \frac{V_A}{I_D}$

thus, $g_m r_{o2} = 2V_A / V_{ov}$
 $\Rightarrow \underline{\underline{A_d = 2(V_A / V_{ov})^2}}$ Q.E.D.

For $V_{ov} = 0.25V$ & $V_A = 20V$
 $A_d = 2(20/0.25)^2 = \underline{\underline{12800 V/V}}$

7.67

$R_{id} = (\beta + 1) 2r_e$; $r_e = \frac{25mV}{50\mu A}$

$\Rightarrow R_{id} = 101 \times 1000 = \underline{\underline{101k\Omega}}$

$R_o = r_{o4} \parallel r_{o2} = \frac{r_o}{2}$; $r_o = \frac{V_A}{I_c}$

$\Rightarrow r_o = \frac{160V}{50\mu A} = 3.2M\Omega$

Thus, $R_o = \underline{\underline{1.6M\Omega}}$

$G_m = g_{m1} = g_{m2} = \frac{50\mu A}{25mV} = \underline{\underline{2\mu A/V}}$

7.68

$G_m = \frac{I/2}{V_T} = \frac{5mA}{V}$

$I = \underline{\underline{250\mu A}}$

$R = \frac{5 - (-5) - V_{BE}}{I}$
 $= \frac{9.3}{0.25} = \underline{\underline{37.2k\Omega}}$

$R_{id} = (\beta + 1) 2r_e$ where,

$r_e = \frac{V_T}{I/2} = \frac{25mV}{0.125mA} = 200\Omega$

$\Rightarrow R_{id} = 151 \times 2 \times 0.2 = \underline{\underline{60.4k\Omega}}$

$r_o = \frac{V_A}{I_c} = \frac{100}{0.125} = 800k\Omega$

$R_o = \frac{r_o}{2} = \underline{\underline{400k\Omega}}$

$A_d = g_m R_o = 5 \times 400 = \underline{\underline{2000 V/V}}$

$I_B = \frac{I/2}{\beta + 1} = \frac{125}{151} = \underline{\underline{0.83\mu A}}$

$V_{icm|max} = V_{C1} + 0.4V$
 $= 5 - 0.7 + 0.4 = \underline{\underline{4.7V}}$

$V_{icm|min} = V_{B5} - 0.4 + 0.7$
 $= -5 - 0.4 + 0.7$
 $= \underline{\underline{-4V}}$

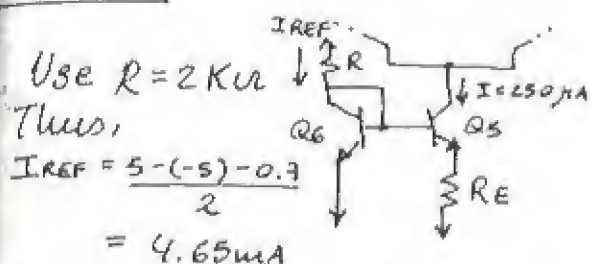
Thus, the input common-mode range is $-4V$ to $+4.7V$
 (where we have assumed that a transistor remains active
 CONT.

even through its base-collector junction is forward biased by 0.4V)

$$R_{icm} \approx (\beta+1) [r_{o5} \parallel r_{o1} \parallel r_{o2}]$$

$$= 151 \times (400 \parallel 800 \parallel 800) = \underline{\underline{30 \text{ k}\Omega}}$$

7.69



Use $R = 2 \text{ k}\Omega$
Thus,

$$I_{REF} = \frac{5 - (-5) - 0.7}{2}$$

$$= 4.65 \text{ mA}$$

$$V_{BE6} - V_{BE5} = V_T \ln(4.65/0.25)$$

$$= 73.1 \text{ mV}$$

$$R_E = 73.1 \text{ mV} / 0.25 \text{ mA}$$

$$= \underline{\underline{292 \Omega}}$$

The only amplifier parameter that changes is R_{icm} . This is because now r_{o5} is:

$$r_{o5} \approx (1 + g_{m5} R_E) r_{o5}$$

$$= (1 + 10 \times 0.292) \times 400$$

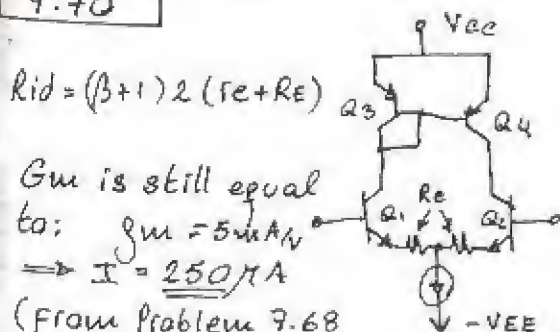
$$= \underline{\underline{1.57 \text{ k}\Omega}}$$

$$\text{Thus, } R_{icm} = (\beta+1) [r_{o5} \parallel r_{o1} \parallel r_{o2}]$$

$$= 151 [1.57 \parallel 0.80 \parallel 0.8]$$

$$= \underline{\underline{48 \text{ k}\Omega}}$$

7.70



$$R_{id} = (\beta+1) 2(r_e + R_E)$$

G_m is still equal to: $g_m = 5 \text{ mA/V}$

$$\Rightarrow I = \underline{\underline{250 \mu\text{A}}}$$

(from Problem 7.68 above)

$$\text{and } r_e = \frac{V_T}{I/2} = 200 \Omega, r_o = 800 \text{ k}\Omega$$

$$\text{If } R_{id} = 100 \text{ k}\Omega \Rightarrow$$

$$100 \text{ k}\Omega = 151 \times 2 \times (200 + R_E)$$

$$\Rightarrow R_E = 131 \Omega$$

To obtain A_d :

$$A_d = G_m \cdot R_o \quad (\text{Egn. 7.165})$$

As in the derivation of R_{o2} in Egn. (7.162), R_{o2} can be found using Egn. (6.159), but this time noting that r_e at the emitter of Q_2 is:

$$r_e + 2R_E$$

Thus,

$$R_{o2} = r_{o2} [1 + g_m((r_e + 2R_E) \parallel r_{\pi 2})]$$

$$R_{o2} = 800 \text{ k}\Omega [1 + 5 \text{ m}((200 + 2 \times 131) \parallel 30.2 \text{ k})]$$

$$R_{o2} = 2620 \text{ k}\Omega$$

$$(\beta+1)r_e$$

$$R_o = R_{o2} \parallel r_{o4}$$

$$= (2620 \parallel 800) \text{ k}\Omega = 613 \text{ k}\Omega$$

$$\Rightarrow A_d = 5 \text{ m} \times 613 \text{ k}\Omega = \underline{\underline{3065 \text{ V/V}}}$$

7.71

$$G_m = g_m = \frac{I/2}{V_T} = \frac{0.5 \text{ mA}/2}{25 \text{ mV}}$$

$$g_m = \underline{\underline{10 \text{ mA/V}}}$$

$$R_o = r_{o2} \parallel r_{o4} = \frac{V_A}{I_{c2}} \parallel \frac{V_A}{I_{c4}} = \frac{1}{2} \frac{V_A}{I/2}$$

$$= \frac{120}{0.5 \text{ mA}} = \underline{\underline{240 \text{ k}\Omega}}$$

$$A_d = G_m R_o = 10 \times 240 = \underline{\underline{2400 \text{ V/V}}}$$

$$R_{id} = 2r_{\pi} \approx 2 \frac{V_T}{I/2} (\beta = \frac{25 \text{ mV} \times 150}{0.5 \text{ mA}})$$

$$R_{id} = \underline{\underline{7.5 \text{ k}\Omega}}$$

For a simple current mirror
CONT.

the output resistance (thus R_{EE}) is so

$$\Rightarrow R_{EE} = \frac{V_A}{I} = \frac{120}{0.5\text{mA}} = 240\text{K}\Omega$$

$$A_{cm} = \frac{-\beta_0}{\beta_3 R_{EE}} = \frac{-(2 \times 240\text{K})}{150 \times 240\text{K}} = -13.3\text{mV/V}$$

$$\text{and, } CMRR = \left| \frac{2400}{-13.3\text{m}} \right| = 180.451$$

i.e. 105 dB

$$\frac{V_i}{V_s} = \frac{R_{id}}{R_{id} + R_s} = \frac{7.5\text{K}}{7.5\text{K} + 10\text{K}} = 0.43\text{V/V}$$

→ Overall gain A:

$$A = \frac{V_i}{V_s} \cdot \frac{V_o}{V_i} = 0.43 \times 2400 = \underline{\underline{1032\text{ V/V}}}$$

7.72

$$i_o = \frac{V_{icm}}{2R_{EE}} - \frac{V_{icm}}{2R_{EE}} \cdot \frac{1}{1 + \frac{2}{\beta_p}}$$

$$= \frac{V_{icm}}{2R_{EE}} + \frac{2/\beta_p}{1 + 2/\beta_p}$$

$$\approx \frac{V_{icm}}{\beta_p R_{EE}} \quad (\beta_p \gg 2) \sim \frac{V_{icm}}{R_{EE}} \quad \text{Q.E.D.}$$

Thus, $G_{mcm} = \frac{i_o}{V_{icm}} = \frac{1}{\beta_p R_{EE}} \quad \text{Q.E.D.}$

$$CMRR = \frac{G_{md}}{G_{mcm}} = \frac{g_m}{1/\beta_p R_{EE}} = g_m \beta_p R_{EE} = \frac{\beta_p \cdot I_{EE}}{2V_T}$$

For $I = 0.2\text{mA}$, $R_{EE} = 1\text{M}\Omega$ and $\beta_p = 25$:

$$CMRR = \frac{\beta_p \cdot I_{EE}}{2V_T} = \frac{25 \times 0.2 \times 1000}{2 \times 0.025} = 10^5 \text{ i.e. } \underline{\underline{100\text{ dB}}}$$

7.73

$$i_o = \frac{V_{icm}}{2R_{EE}} - \frac{V_{icm}}{2R_{EE}} \cdot \frac{1}{1 + \frac{2}{\beta_p}}$$

$$\approx \frac{V_{icm}}{2R_{EE}} \left(1 - \left(1 - \frac{2}{\beta_p} \right) \right)$$

$$= \frac{V_{icm}}{\beta_p^2 R_{EE}} \quad \text{Q.E.D.}$$

$$G_{mcm} = \frac{i_o}{V_{icm}} = \frac{1}{\beta_p^2 R_{EE}}$$

$$CMRR = \frac{G_{md}}{G_{mcm}} = \beta_p^2 g_m R_{EE} = \frac{\beta_p^2 I_{EE}}{2V_T}$$

Thus,

$$CMRR = \frac{(25)^2 \times 0.2 \times 1000}{2 \times 0.025} = 25 \times 10^5$$

or 128 dB

7.74

$$A_{vo} = G_m R_o$$

$$G_m = g_m$$

$$R_o = R_{oc} \parallel R_{ow}$$

where R_{oc} is the output resistance of the cascode stage K

R_{ow} the output resistance of the Wilson stage

CONT.

$$R_{oc} = \beta f_o \quad \& \quad R_{ow} = \beta \frac{f_o}{2}$$

$$\Rightarrow R_o = \beta_{ro} \parallel \frac{\beta_{ro}}{2} = \frac{\beta_{ro}}{2} \cdot \beta_{ro}$$

$$= \frac{\beta_{ro}}{2 \times \frac{3}{2}} = \frac{\beta_{ro}}{3} \beta_{ro} \left(1 + \frac{1}{2}\right)$$

$$\Rightarrow A_{00} = G m^2 R_0 = g m \frac{B r_0}{3} \quad \text{Q.E.D}$$

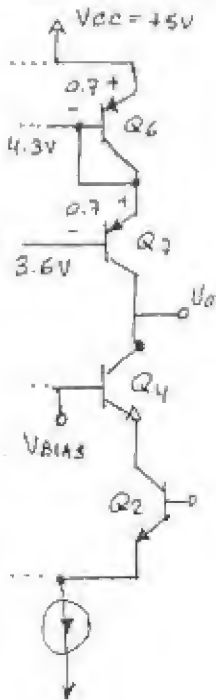
For: $I = 0.4 \text{ mA}$, $\beta = 100$, $V_A = 120 \text{ V}$

$$A_{vo} = \frac{I/2}{V_T} \cdot \frac{\beta \cdot V_A}{3 \cdot I/2} = \frac{\beta}{3} \frac{V_A}{V_T}$$

$$= \frac{100}{3} \times \frac{120V}{25mV} = \underline{\underline{160000}}$$

i.e. 104 dB

7.75



(2) $V_{Omax} - V_{B7} = 0.4V$
but: $V_{B7} = 5 - 2 \times 0.7V$
 $= 3.6V$

$$\Rightarrow V_{o \max} = 3.6 + 0.4 = \underline{4.0V}$$

(b) For a 1.5V max. positive swing the DC bias at the output should be:

$$V_{O_{DC}} = 4 - 1.5 = \underline{\underline{2.5V}}$$

(c) In the edge of saturating Q_4

$$V_{BIAS} - V_{Omin} = 0.4V$$

$$\rightarrow V_{onin} = V_{BIAS} - 0.4V$$

If V_{out} is: V_{out} = 1.5
2.5 - 1.5 = 1V

$$\Rightarrow V_{BIAS} = 1.4V.$$

(d) If $V_{BIAS} = 1.4V$

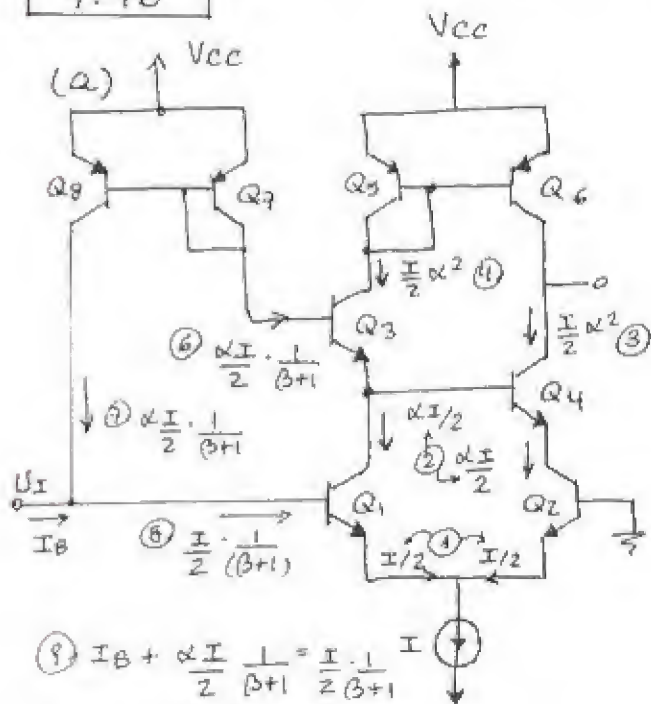
$$\Rightarrow V_{C_2} = 1.4 - 0.7 = 0.7V$$

The upper limit of U_{lim} is such that brings Q_2 to the edge of saturating.

$$V_{icm\max} - V_{E2} = 0.4 \text{ V}$$

$$\Rightarrow U_{\text{lem min}} = 0.4 + 0.7 = \underline{\underline{1.1V}}$$

7.76



$$(9) I_B + \frac{\alpha I}{2} \frac{1}{\beta + 1} = \frac{I}{2} \frac{1}{\beta + 1} I$$

$$\Rightarrow I_B = \frac{I}{2} \frac{1}{(\beta+1)} (1-\alpha) = \frac{I}{2} \frac{1}{(\beta+1)^2}$$

Without $Q_8 \times Q_7$

$$I_B = \frac{I}{2} \cdot \frac{1}{(\beta + 1)}$$

thus, the input or current is reduced by $\times 1/(B+1)$

(b) Without Q_8 & Q_7 :

$$R_{in} = 2r_{\pi 1,2} \quad ; \quad (R = \frac{V_T}{I_B} = \frac{V_T 2\beta + 1}{I})$$

$$\Rightarrow R_{in} = \frac{4V_T}{I} (\beta_H)$$

CONT.

With $Q_8 \times Q_7$: $R_{in} = 2(\pi \parallel r_{o8})$
 where $r_{o8} = \frac{V_A \cdot 2(\beta+1)}{\alpha I}$

$$\rightarrow R_{in} = \frac{4V_T}{I} (\beta+1) \parallel \frac{V_A \cdot 2(\beta+1)}{\alpha I}$$

Solving, yields:

$$R_{in} = \frac{4V_T}{I} (\beta+1) \cdot \frac{V_A}{2\alpha V_T + V_A}$$

but $\frac{V_A}{2\alpha V_T + V_A} \approx 1 \Rightarrow R_{in} = \frac{4V_T(\beta+1)}{I}$

Just like when $Q_8 \times Q_7$ are not present.

7.77

For the Wilson current source

$$\frac{I_4}{I_3} = \frac{1}{1 + 2/\beta p^2}$$

Since $I_3 = \alpha I/2$

$$\rightarrow I_4 = \frac{\alpha I/2}{1 + 2/\beta p^2}$$

$$\Delta i = \frac{\alpha I}{2} - \frac{\alpha I/2}{1 + 2/\beta p^2}$$

$$= \frac{\alpha I}{2} \cdot \frac{2/\beta p^2}{1 + 2/\beta p^2} = \alpha I \cdot \frac{1}{\beta p^2 + 2}$$

$$\approx \frac{\alpha I}{\beta p^2}$$

thus, $V_{os} = \frac{-\Delta i}{G_m}$ with $G_m = g_m = \frac{\alpha I/2}{V_T}$

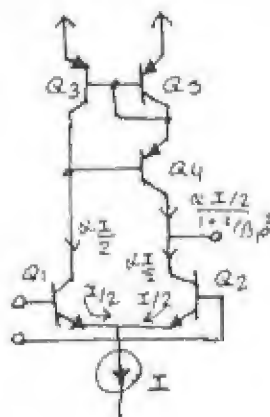
$$\Rightarrow V_{os} = -\frac{\alpha I/\beta p^2}{\alpha I/2V_T} = -\frac{2V_T}{\beta p^2}$$

For $\beta = 50$:

$$V_{os} = -\frac{2 \times 25mV}{(50)^2} = -20\mu V$$

7.78

To obtain maximum positive swing



V_{bias} must be as low as possible
 To keep the top current sources out of saturation:

$$V_{cc} - 0.2 - 0.7 = V_{bias \max}$$

$$V_{bias \max} = 4.1V$$

$$\text{And: } V_o - V_{bias \min} = +0.4V$$

$$\text{Since } V_o \sim 0 \Rightarrow V_{bias \min} = -0.4V$$

\Rightarrow Range of V_{bias} is:

$$(-0.4 \leq V_{bias} \leq 4.1)V$$

$$\text{For: } I = 0.4mA, \beta_p = 50, \beta_n = 150$$

$$\times V_A = 120$$

$$G_m = g_{m1} = \frac{0.2mA}{25mV} = \frac{8mA}{V}$$

For the folded cascode: $R_{o4} = \beta_4 r_{o4}$

For the Wilson mirror: $R_{o5} = \beta_5 \frac{r_{o5}}{2}$

$$\Rightarrow R_o = [\beta_4 \cdot r_{o4} \parallel \beta_5 \cdot \frac{r_{o5}}{2}]$$

$$r_{o4} = r_{o5} = 120 / 0.2mA = 600k\Omega$$

$$\rightarrow R_o = [50 \times 600k \parallel 150 \times \frac{600k}{2}]$$

$$= [30M \parallel 45M]$$

$$= 18M\Omega$$

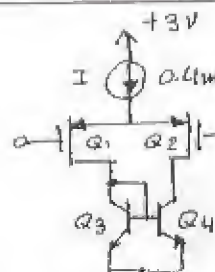
$$A_d = G_m R_o = \frac{8mA}{V} \times 18M\Omega = 14400$$

7.79

$$K_p' W/L = 6.4mA/V^2$$

$$|V_{Ap}| = 10V$$

$$V_{ANPN} = 120$$



$$R_o = r_{o2} \parallel r_{o4} = \frac{V_{Ap}}{I/2} \parallel \frac{120}{I/2}$$

$$R_o = (10/0.2m) \parallel (120/0.2m) = 4k\Omega$$

$$G_m = g_{m1} = \sqrt{I \times K_p' W/L}$$

$$= \sqrt{0.4mA \times 6.4mA/V^2}$$

$$\Rightarrow G_m = \frac{1.6mA}{V}$$

$$A_d = G_m \times R_o = \frac{1.6mA}{V} \times 46k\Omega$$

$$\Rightarrow A_d = 73.6 V/V$$

7.80

$$K_n'(W/L) = 128 \mu A \times 25 = 3.2 \text{ mA/V}^2$$

$$(a) V_{ov} = \sqrt{\frac{I}{K_n'(W/L)}} = \sqrt{\frac{0.2}{3.2}} = \underline{0.25 \text{ V}}$$

$$g_m = \frac{I}{V_{ov}} = \frac{0.2 \text{ mA}}{0.25 \text{ V}} = \underline{0.8 \text{ mA/V}}$$

$$(b) A_d = g_m(R_D || r_o)$$

$$\text{where } r_o = \frac{V_A}{I/2} = \frac{20}{0.2/2} = 200 \text{ k}\Omega$$

$$\Rightarrow A_d = 0.8 \text{ m} \times (20 \text{ k} || 200 \text{ k}) = \underline{14.54 \text{ V/V}}$$

(c) For a CS amplifier when R_{sig} is low:

$$f_H = \frac{1}{2\pi (C_L + C_{gd}) R_L'}$$

$$\text{where } R_L' = R_D || r_o = 20 \text{ k} || 200 \text{ k} = 18.18 \text{ k}\Omega$$

$$\text{and } C_L' = C_L + C_{db}$$

Since for a grounded source terminal C_{db} is in parallel with the load.

$$\rightarrow C_L' = 90 + 5 = 95 \text{ fF}$$

thus,

$$f_H = \frac{1}{2\pi (95 + 5) 10^{-15} \times 18.18 \text{ k}} = \underline{87.54 \text{ MHz}}$$

(d) Using the open-circuit time-constants method for $R_S = 20 \text{ k}\Omega$

$$f_H = \frac{1}{2\pi \tau_H}$$

$$\text{where } \tau_H = C_{gs} R_S + C_{gd} [R_S (1 + g_m R_L') + R_L'] + C_L R_L'$$

thus,

$$\tau_H = 30 \text{ f} \times 20 \text{ k} + 5 \text{ f} [20 \text{ k} (1 + 0.8 \times 18.18) + 18.18 \text{ k}] + (90 \text{ f} + 5 \text{ f}) \times 18.18 \text{ k}$$

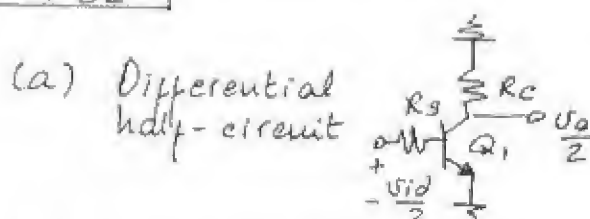
$$\tau_H = 0.6 \text{ ns} + 1.64 \text{ ns} + 1.72 \text{ ns} = 3.96 \text{ ns}$$

$$\Rightarrow f_H = \frac{1}{2\pi \times 3.96 \text{ ns}} = \underline{40.2 \text{ MHz}}$$

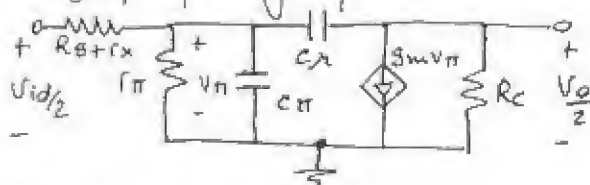
7.81

$$f_z = \frac{1}{2\pi C_{gs} R_{gs}} = \frac{1}{2\pi (0.2 \text{ p})(100 \text{ k})} = \underline{7.95 \text{ MHz}}$$

7.82



High-frequency equivalent circuit



$$(b) I_E = 0.5 \text{ mA} \rightarrow g_m = \frac{0.5}{25}$$

$$g_m = 20 \text{ mA/V}$$

$$r_{\pi} = \frac{\beta}{g_m} = \frac{100}{20 \text{ m}} = 5 \text{ k}\Omega$$

$$C_{\pi} + C_{\mu} = \frac{20 \times 10^{-3}}{2\pi \times 600 \times 10^6} = 5.3 \text{ pF}$$

$$C_{\mu} = 0.5 \text{ p} \Rightarrow C_{\pi} = 4.8 \text{ pF}$$

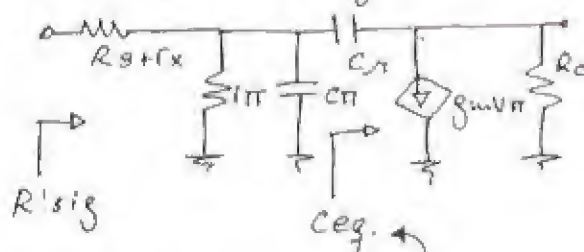
Now, $R_S = 10 \text{ k}\Omega$, $R_C = 10 \text{ k}\Omega$, $r_x = 100$
For this common-emitter amplifier (Refer to Section..
CONT.

5.9 Equ. (5.164)

$$\begin{aligned}\frac{V_o}{V_i} &= \frac{-\beta \pi}{\beta \pi + (R_s + r_x)} \cdot g_m R_c \\ &= \frac{-5K}{5K + (10K + 100)} \cdot 20m \times 10K \\ &= \underline{\underline{-66.22 \text{ V/V}}}\end{aligned}$$

(c) Refer to Section 5.9,
Eqs (5.176), (5.173), (5.168)
From Equ. (5.176):

$$f_H = \frac{1}{2\pi C_{in} R'_{sig}}$$



where: $C_{in} = C_{\pi} + C_{eq}$
Using Miller's theorem
 $C_{eq} = C_{\mu} (1 + g_m R_c)$
and
 $R'_{sig} = (R_s + r_x) \parallel r_{\pi}$

Thus,

$$\begin{aligned}f_H &= \frac{1}{2\pi [(R_s + r_x) \parallel r_{\pi}] [C_{\pi} + C_{\mu} (1 + g_m R_c)]} \\ &= \frac{1}{2\pi ((10K + 100) \parallel 5K) (4.8p + 0.5p (1 + 20 \times 10))} \\ &= \underline{\underline{452 \text{ KHz}}}\end{aligned}$$

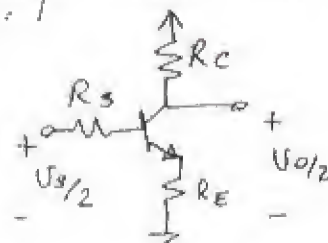
$$GBW = 66.22 \times 452K = \underline{\underline{30 \text{ MHz}}}$$

7.83

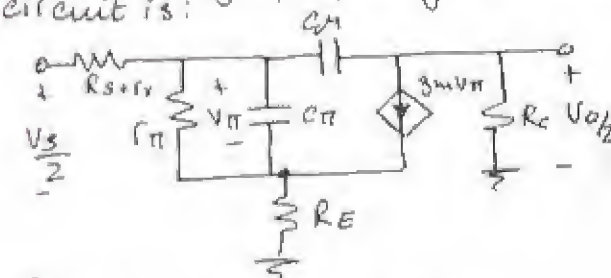
From problem 7.82 above:

$$\begin{aligned}g_m &= 20 \text{ mA/V} \quad r_{\pi} = 5K\Omega \quad C_{\pi} = 4.8 \text{ pF} \\ C_{\mu} &= 0.5 \text{ pF} \quad R_s = 5K\Omega \quad R_c = 10K\Omega \\ r_x &= 100\Omega\end{aligned}$$

If we add an emitter resistor,
then the equivalent half-circuit is:



And the high-frequency equivalent circuit is:



For this circuit the low-frequency gain is:

$$A_o = \frac{V_o}{V_s} = \frac{-(\beta + 1) \cdot (r_e + R_E)}{(R_s + r_x) + (\beta + 1)(r_e + R_E)} \times \frac{R_c}{R_c + r_e}$$

obtained by reflecting emitter resistance to the base

gain V_o/V_i as in eq 5.13

$$\text{where } r_e = \frac{V_T}{I_E} = \frac{25}{0.5} = 50\Omega$$

$$\begin{aligned}A_o &= \frac{-101 \times (50 + 100)}{(10K + 100) + 101 \times (50 + 100)} \times \frac{100 \times 10K}{101 \times (100 + 50)} \\ &= \underline{\underline{-39.6 \text{ V/V}}}\end{aligned}$$

Using the method of open-circuit time constants:

$$f_H = 1 / (2\pi (C_{\pi} R_{\pi} + C_{\mu} R_{\mu}))$$

CONT.

Referring to the high-frequency equivalent circuit.

$$R_{\pi} = r_{\pi} \parallel \frac{R_s + r_x + R_E}{1 + g_m R_E}$$

$$= 5K \parallel \frac{10K + 100 + 100}{1 + 20m \times 100}$$

$$= 5K \parallel 3.4K = 2.02K\Omega$$

To obtain R_f :

$$R_{in} = (\beta + 1)(R_E + r_e)$$

$$= 101 \times (100 + 50) = 15.15K\Omega$$

$$G_m = \frac{g_m}{1 + g_m R_E} = \frac{20m}{1 + 20m \times 100}$$

$$= 6.67m$$

Thus,

$$R_f = [(R_s + r_x) \parallel R_{in}] (1 + G_m R_C) + R_C$$

$$= [(10K + 100) \parallel 15.15K] \cdot (1 + 6.67 \times 10) + 10K$$

$$= 420.26K\Omega$$

Thus, $C_{\pi} R_{\pi} + C_f R_f =$

$$= 4.8pF \times 2.02K\Omega + 0.5pF \times 420.26K$$

$$= 219.8ns \approx 220ns$$

$$\Rightarrow f_H = \frac{1}{2\pi \times 220ns} = 723.4KHz$$

$$GBW = 39.6 \times 723.4K = 28.6MHz$$

Approx. the same as in problem 7.82 above.

7.84

From the solution of problem 7.81:

$$g_m = 20mA/V \quad r_e = 50\Omega \quad r_{\pi} = 5K\Omega$$

$$C_{\pi} = 4.8pF \quad C_f = 0.5pF \quad R_s = 10K\Omega$$

$$R_C = 10K\Omega \quad r_x = 100\Omega$$

$$f_H = 1/(2\pi \tau_H) = 1 \times 10^6 Hz$$

$$\Rightarrow \tau_H = 1/(2\pi \times 10^6)$$

$$= 159.15ns$$

$$\text{But: } \tau = C_{\pi} R_{\pi} + C_f R_f$$

where

$$R_{\pi} = r_{\pi} \parallel \left(\frac{R_s + r_x + R_E}{1 + g_m R_E} \right)$$

$$= \frac{1}{\frac{1}{r_{\pi}} + \frac{1 + g_m R_E}{R_s + r_x + R_E}}$$

$$= \frac{1}{\frac{1}{5K} + \frac{1 + g_m R_E}{10.1K + R_E}}$$

$$R_f = [(R_s + r_x) \parallel R_{in}] (1 + G_m R_C) + R_C$$

$$\text{with: } R_{in} = (\beta + 1)(R_E + r_e)$$

$$G_m = g_m / (1 + g_m R_E)$$

thus,

$$R_f = \frac{1}{\frac{1}{R_s + r_x} + \frac{1}{(\beta + 1)(R_E + r_e)}} \cdot \left(1 + \frac{g_m R_C}{1 + g_m R_E} \right) + R_C$$

$$= \frac{1 + g_m R_C + g_m R_E}{\frac{1 + g_m R_E}{R_s + r_x} + \frac{1 + g_m R_E}{(\beta + 1)(R_E + r_e)}} + R_C$$

$$= \frac{1 + g_m R_E}{(\beta + 1)(R_E + \frac{1}{g_m})}$$

$$\Rightarrow = \frac{g_m}{\beta + 1} \cdot \frac{(1 + g_m R_E)}{(1 + g_m R_E)}$$

and, since $r_{\pi} = \beta / g_m$

$$\Rightarrow \frac{g_m}{\beta + 1} \approx \frac{1}{r_{\pi}}$$

thus,

$$R_f = \frac{1 + g_m R_C + g_m R_E}{\frac{1 + g_m R_E}{R_s + r_x} + \frac{1}{r_{\pi}}} + R_C$$

CONT.

$$159.15 \mu s = \frac{4.8 \text{ pF}}{\frac{1}{5 \text{ K}} + \frac{1+g_m R_e}{10.1 \text{ K} + R_e}} + \frac{0.5 \text{ pF} (1+200+g_m R_e)}{\frac{1+g_m R_e}{10.1 \text{ K}} + \frac{1}{5 \text{ K}}} + \frac{0.5 \text{ pF} \times 10 \text{ K}}{5 \mu s}$$

Assuming that $R_e \ll 10.1 \text{ K}$

$$154.15 \mu s = \frac{4.8 \text{ pF} + 0.5 \text{ pF} (1+200+g_m R_e)}{\frac{1}{5 \text{ K}} + \frac{1+g_m R_e}{10.1 \text{ K}}}$$

$$(154.15 \mu s) \left(\frac{1}{5 \text{ K}} + \frac{1+g_m R_e}{10.1 \text{ K}} \right) = 4.8 \text{ pF} + 0.5 \text{ pF} (1+g_m R_e) + 100 \text{ pF}$$

Solving for $1+g_m R_e$ yields:
 $1+g_m R_e = 5 \Rightarrow R_e = \underline{\underline{200 \Omega}}$

The DC gain is:

$$A_0 = \frac{-101 \times (50+200)}{(10 \text{ K} + 100) + 101 \times (50+200)} \times \frac{100}{101} \times \frac{10 \text{ K}}{(200+50)} = \underline{\underline{-28.28 \text{ V/V}}}$$

$$R_{in} = 101 \times (200+50) = 25.25 \text{ K}\Omega$$

$$G_m = 20 \text{ m} / (1+20 \text{ m} \times 200) = 4 \text{ m}$$

$$R_{\pi} = ((10 \text{ K} + 100) \parallel 25.25 \text{ K}) (1+4 \times 10) + 10 \text{ K} = 305,785 \Omega$$

$$R_{\pi} = 5 \text{ K} \parallel \frac{10 \text{ K} + 100 + 200}{1+20 \text{ m} \times 200} = 1459 \Omega$$

$$\tau_H = 1459 \times 4.8 \text{ p} + 305,785 \times 0.5 \text{ p} = 159.8 \mu s$$

$$f_H = \frac{1}{2\pi \tau_H} = 0.99 \text{ MHz} \sim \underline{\underline{1 \text{ MHz}}}$$

$$GBW = 28.28 \times 1 = \underline{\underline{28.28 \text{ MHz}}}$$

7.85

$$I = 0.6 \text{ mA}$$

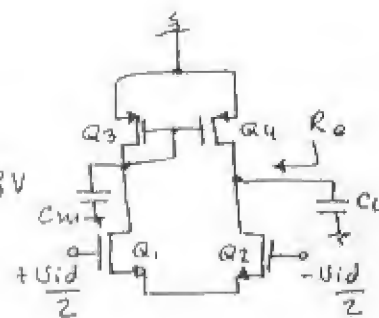
$$V_{ovn} = 0.3 \text{ V}$$

$$V_{ovp} = 0.5 \text{ V}$$

$$V_{An} = |V_{Ap}| = 9 \text{ V}$$

$$C_m = 0.1 \text{ pF}$$

$$C_L = 0.2 \text{ pF}$$



All Q 's are identical:

$$r_o = \frac{V_A}{I_D} = \frac{9}{0.3 \text{ m}} = 30 \text{ K}\Omega$$

$$g_m = \frac{2I_D}{V_{ov}} \Rightarrow g_{m1,2} = \frac{0.6 \text{ m}}{0.3} = 2 \text{ mA/V}$$

$$g_{m3,4} = \frac{0.6 \text{ m}}{0.5} = 1.2 \text{ mA/V}$$

The low frequency differential gain is:

$$A_d = g_{m1,2} (r_{o2} \parallel r_{o4})$$

$$= 2 \text{ mA/V} (30 \text{ K} \parallel 30 \text{ K}) = \underline{\underline{30 \text{ V/V}}}$$

From Equ. (7.192)

$$f_{p1} = 1/(2\pi C_L R_0)$$

$$\text{where } R_0 = r_{o2} \parallel r_{o4} = 15 \text{ K}\Omega$$

$$f_{p1} = \frac{1}{2\pi \times 0.2 \text{ p} \times 15 \text{ K}} = \underline{\underline{53 \text{ MHz}}}$$

$$(7.193) f_{p2} = \frac{g_{m3}}{2\pi C_m} = \frac{1.2 \text{ mA/V}}{2\pi \times 0.1 \text{ p}} = \underline{\underline{1.9 \text{ GHz}}}$$

$$(7.194) f_z = \frac{2g_{m3}}{2\pi C_m} = \frac{2 \times 1.2 \text{ m}}{2\pi \times 0.1 \text{ p}} = \underline{\underline{3.8 \text{ GHz}}}$$

7.86

The CMRR will have.. CONT

poles at 500KHz and at

$$\frac{1}{2\pi \times 10^6 \times 10 \times 10^{-12}} = \underline{15.9 \text{ KHz}}$$

7.87

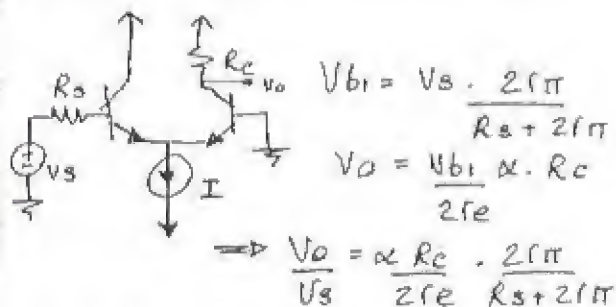
From the solution to Problem 7.82 above:

$$g_m = 20 \text{ mA/V} \quad r_e = 50 \Omega \quad r_{\pi} = 5 \text{ K}\Omega$$

$$C_{\pi} = 4.8 \text{ pF} \quad C_H = 0.5 \text{ pF} \quad R_s = 10 \text{ K}\Omega$$

$$R_c = 10 \text{ K}\Omega$$

Here we neglect r_x , i.e. $r_x = 0$.



$$V_{b1} = V_s \cdot \frac{2r_{\pi}}{R_s + 2r_{\pi}}$$

$$V_o = \frac{V_{b1}}{2r_e} \cdot R_c$$

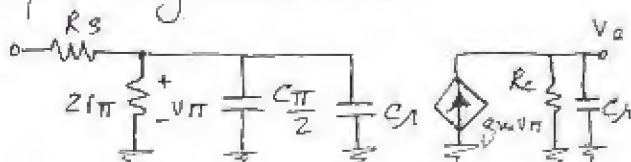
$$\Rightarrow \frac{V_o}{V_s} = \alpha \frac{R_c}{2r_e} \cdot \frac{2r_{\pi}}{R_s + 2r_{\pi}}$$

$$= \frac{\alpha \cdot R_c \cdot r_e (\beta + 1)}{r_e (R_s + 2r_{\pi})} = \frac{\alpha R_c}{\frac{R_s}{\beta + 1} + 2r_e}$$

$$= \frac{\beta R_c}{R_s + 2r_{\pi}}$$

$$A_o = \frac{V_o}{V_s} = \frac{100 \times 10 \text{ K}}{10 \text{ K} + 2 \times 5 \text{ K}} = \underline{50 \text{ V/V}}$$

Using the equivalent circuit of Fig 6.57, i.e.



thus,

$$f_{p1} = \frac{1}{2\pi (R_s \parallel 2r_{\pi}) (\frac{C_{\pi}}{2} + C_H)}$$

$$= \frac{1}{2\pi (10 \text{ K} \parallel 10 \text{ K}) (\frac{4.8 \text{ pF}}{2} + 0.5 \text{ pF})}$$

$$= \underline{11 \text{ MHz}}$$

and, $f_{p2} = \frac{1}{2\pi R_c C_H}$

$$= \frac{1}{2\pi \times 10 \text{ K} \times 0.5 \text{ pF}} = 31.8 \sim \underline{32 \text{ MHz}}$$

thus, $f_H = \frac{1}{\sqrt{(\frac{1}{11})^2 + (\frac{1}{32})^2}} = \underline{10.4 \text{ MHz}}$

7.88

$$V_{G1} = V_s \cdot \frac{2/g_m}{2/g_m + R_s} \quad I = \frac{V_{G1}}{2/g_m}$$

$$V_o = I R_o = \frac{V_{G1} \times R_o}{2/g_m}$$

$$= \frac{V_s \times 2/g_m \cdot R_o}{2/g_m + R_s}$$

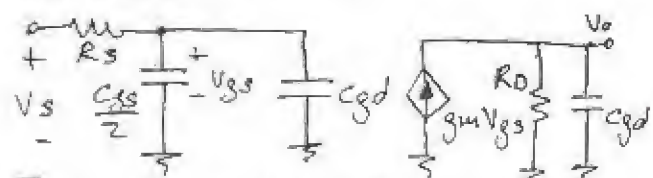
$$= \frac{V_s \cdot R_o}{2/g_m + R_s}$$

$$\Rightarrow A_o = \frac{V_o}{V_s} = \frac{g_m R_o}{2 + g_m R_s}$$

$$g_m = \frac{200 \mu\text{A}}{0.25 \text{ V}} = 0.8 \frac{\text{mA}}{\text{V}}$$

$$\Rightarrow A_o = \frac{0.8 \times 50}{2 + 0.8 \times 200} = 0.24 \text{ V/V}$$

The high-frequency equivalent circuit is:



Thus, the pole at the input has a frequency f_{p1} :

CONT.

$$f_{p1} = \frac{1}{2\pi R_s \times (\frac{C_{gs}}{2} + C_{gd})}$$

$$= \frac{1}{2\pi \times 200K \times (\frac{1}{2} + 1)p}$$

$$= \underline{530 KHz}$$

and the pole at the output has a frequency f_{p2} :

$$f_{p2} = \frac{1}{2\pi R_o C_{gd}} = \frac{1}{2\pi \times 50K \times 1p}$$

$$= \underline{3.18 MHz}$$

Thus $f_H \approx \frac{1}{\sqrt{(\frac{1}{530K})^2 + (\frac{1}{3.18M})^2}}$

$$= \underline{523 KHz}$$

Notice that this low value of f_H is due to the large value of R_s .

7.89

Refer to Fig. P7.89.
It can be shown that this circuit is equivalent to that of Problem 7.87 above.

$$g_m = \frac{0.1mA}{25mV} = \frac{4mA}{V} \quad r_e \approx 250\Omega$$

$$r_{\pi} = \frac{\beta}{g_m} = \frac{200}{4mA/V} = 50K\Omega$$

$$A_o = \frac{\alpha R_c}{\frac{R_s}{\beta+1} + 2r_e} = \frac{\frac{200}{201} \times 50K}{\frac{50K}{201} + 2 \times 250}$$

$$= \underline{66.44 V/V}$$

$$2\pi f_T = \frac{g_m}{C_{\pi} + C_L} \Rightarrow C_{\pi} + C_L = \frac{4mA}{2\pi \times 600}$$

$$C_{\pi} + C_L = 1.06pF$$

$$\text{Since } C_L = 0.2pF \rightarrow C_{\pi} = 0.86pF$$

$$f_{p1} = \frac{1}{2\pi (R_s \parallel 2r_{\pi}) (\frac{C_{\pi}}{2})}$$

$$= \frac{1}{2\pi (50K \parallel 2 \times 50K) (\frac{0.86}{2})p}$$

$$= \underline{7.58 MHz}$$

$$f_{p2} = \frac{1}{2\pi R_C C_L} = \frac{1}{2\pi \times 50K \times 0.2p}$$

$$= \underline{15.9 MHz}$$

Thus the estimate of f_H is:

$$f_H = \frac{1}{\sqrt{(\frac{1}{7.58})^2 + (\frac{1}{15.9})^2}}$$

$$= \underline{6.84 MHz}$$

7.90

To ensure that the op amp will not have a systematic offset voltage, use Eqn. (7.201)

$$\frac{(W/L)_6}{(W/L)_4} = 2 \frac{(W/L)_7}{(W/L)_5}$$

$$\Rightarrow (W/L)_6 = 2 \times \frac{(60/0.5)(10/0.5)}{(60/0.5)}$$

$$\Rightarrow (W/L)_6 = \underline{(20/0.5)}$$

Since Q_8 and Q_5 are matched $I = I_{REF} = 225\mu A$
Thus Q_1, Q_2, Q_3 and Q_4

CONT.

each conducts a current equal to $I/2 = 112.5 \mu A$.

Since Q_7 is matched to Q_5 and Q_8 , the current in Q_7 is equal to $I_{REF} = 225 \mu A$.

Finally Q_6 conducts an equal current of $225 \mu A$.

Thus,

$$I_{D1} = 112.5 \mu A \quad I_{D5} = 225 \mu A$$

$$I_{D2} = 112.5 \mu A \quad I_{D6} = 225 \mu A$$

$$I_{D3} = 112.5 \mu A \quad I_{D7} = 225 \mu A$$

$$I_{D4} = 112.5 \mu A \quad I_{D8} = 225 \mu A$$

To find $|V_{ov}|$ we use:

$$I_D = \frac{1}{2} \mu_{COX} (W/L) V_{ov}^2$$

then we find $|V_{GS}|$ from:

$$|V_{GS}| = |V_{t1}| + |V_{ov}|$$

this results in:

$$|V_{ov1}| = 0.25 V \quad |V_{GS1}| = 1 V$$

$$|V_{ov2}| = 0.25 V \quad |V_{GS2}| = 1 V$$

$$|V_{ov3}| = 0.25 V \quad |V_{GS3}| = 1 V$$

$$|V_{ov4}| = 0.25 V \quad |V_{GS4}| = 1 V$$

$$|V_{ov5}| = 0.25 V \quad |V_{GS5}| = 1 V$$

$$|V_{ov6}| = 0.25 V \quad |V_{GS6}| = 1 V$$

$$|V_{ov7}| = 0.25 V \quad |V_{GS7}| = 1 V$$

$$|V_{ov8}| = 0.25 V \quad |V_{GS8}| = 1 V$$

To find g_m : $g_m = 2I_D / |V_{ov}|$
and r_o : $r_o = |V_A| / I_D$

Thus:

$$g_{m1} = 0.9 \text{ mA/V} \quad r_{o1} = 80 \text{ K}\Omega$$

$$g_{m2} = 0.9 \text{ mA/V} \quad r_{o2} = 80 \text{ K}\Omega$$

$$g_{m3} = 0.9 \text{ mA/V} \quad r_{o3} = 80 \text{ K}\Omega$$

$$g_{m4} = 0.9 \text{ mA/V} \quad r_{o4} = 80 \text{ K}\Omega$$

$$g_{m5} = 1.8 \text{ mA/V} \quad r_{o5} = 40 \text{ K}\Omega$$

$$g_{m6} = 1.8 \text{ mA/V} \quad r_{o6} = 40 \text{ K}\Omega$$

$$g_{m7} = 1.8 \text{ mA/V} \quad r_{o7} = 40 \text{ K}\Omega$$

$$g_{m8} = 1.8 \text{ mA/V} \quad r_{o8} = 40 \text{ K}\Omega$$

$$A_1 = -g_{m1} (r_{o2} || r_{o4})$$

$$= -0.9 \text{ mA/V} (80 || 80) \text{ K}\Omega$$

$$= -36 \text{ V/V}$$

$$A_2 = -g_{m6} (r_{o5} || r_{o7})$$

$$= -1.8 \text{ mA/V} (40 || 40) \text{ K}\Omega$$

$$= -36 \text{ V/V}$$

Thus, the DC open-loop gain is:

$$A_0 = A_1 A_2 = (-36) \times (-36)$$

$$= 1296 \text{ V/V}$$

$$\rightarrow 62.25 \text{ dB}$$

Input common-mode range:

lower limit is when the input is such that Q_1 & Q_2 leave the saturation region.

$$V_{D1} = -V_{SS} + V_{GS3}$$

$$= -1.5 + 1 = -0.5 \text{ V}$$

$$V_{in, \min} = -0.5 - |V_{t1}|$$

$$= -0.5 - 0.75 = -1.25 \text{ V}$$

The upper limit is the value of V_{in} at which Q_5 leaves the saturation region.

$$V_{GS5, \max} = +1.5 - |V_{ov5}|$$

$$= 1.25 \text{ V}$$

$$\rightarrow V_{in, \max} = 1.25 - 1 = +0.25 \text{ V}$$

Input range is: -1.25 to 0.25 V

Output voltage range:

V_{omax} is the value at which Q_7 leaves saturation.

$$V_{DD} - |V_{ov7}| = +1.5 - 0.25$$

$$= 1.25 \text{ V}$$

The lowest V_o is the value at which Q_6 leaves saturation

$$\text{i.e. } -V_{SS} + V_{ov6} = -1.5 + 0.25$$

$$= -1.25 \text{ V}$$

The output range is

$$-1.25 \text{ to } +1.25 \text{ V}$$

7.91

$$I = \frac{1}{2} K V_{ov}^2$$

$$(a) V_{ov} = \sqrt{\frac{2I}{K}}$$

If K increases by 4 $\rightarrow V_{ov}$ decreases by $\frac{1}{2}$

$$g_m = 2I/V_{ov} = K \cdot V_{ov}$$

\rightarrow If K increases by 4 g_m increases by $\times 2$

$$(b) A_1 = g_m R_{o1}$$

$\Rightarrow A_1$ increases $\times 2$ and so A_o

(c) Offsets due to V_t mismatches are unaffected. Others reduced $\times \frac{1}{2}$ since A_o increases $\times 2$

$$(d) A_o f_p = f_T \Rightarrow f_p = \frac{f_T}{A_o}$$

and is reduced $\times \frac{1}{2}$
 $\Rightarrow C_c$ must be doubled.

7.92.

$$I_{D7} = \frac{W_7}{W_8} I_{REF} = \frac{50}{40} \times 90 \mu A$$

$$= 112.5 \mu A //$$

$$\text{Output offset current} = I_{D7} - I_{D6}$$

$$= 112.5 - 90 = 22.5 \mu A$$

$$\Rightarrow V_o = 22.5 \mu (106 \parallel 107)$$

$$107 = \frac{10}{112.5 \mu} = 88.9 K\Omega$$

$$\Rightarrow V_o = 22.5 \mu (11K \parallel 88.9K)$$

$$= 1.11 V$$

$$V_{os} = \frac{V_o}{A_o} = \frac{1.11 V}{1109} = \underline{\underline{1 mV}}$$

7.93

$$\text{Offset current} = I_{D2} - I_{D4}$$

$$= I_{D3} - I_{D4}$$

$$I_{D3} = \frac{K}{2} (V_{GS} - V_t)^2$$

$$I_{D4} = \frac{K}{2} (V_{GS} - (V_t + \Delta V_t))^2$$

$$I_o = I_{D3} - I_{D4}$$

$$= \frac{K}{2} [(V_{GS} - V_t - V_{GS} + V_t + \Delta V_t) \times (V_{GS} - V_t + V_{GS} - V_t - \Delta V_t)]$$

$$= \Delta V_t \cdot \frac{K}{2} (2V_{GS} - 2V_t - \Delta V_t)$$

$$\approx K (V_{GS} - V_t) \cdot \Delta V_t$$

$$I_o = \underline{\underline{g_{m3} \Delta V_t}}$$

$$\text{Recall } I_o = G_{m1} \cdot V_{os}$$

$$\text{and } G_{m1} = g_{m1}$$

$$\Rightarrow V_{os} = \frac{g_{m3}}{g_{m1}} \cdot \Delta V_t$$

$$\text{For } \Delta V_t = 2 mV$$

$$V_{os} = \frac{0.3 m}{0.3 m} \times 2 m = \underline{\underline{2 mV}}$$

7.94

$$\text{From Eqn. (7.211)} \quad Wt = \frac{G_{m1}}{C_c}$$

$$G_{m1} = g_{m1} = 1 mA/V$$

$$\text{For } f_T = 50 MHz$$

$$C_c = \frac{1 mA/V}{2\pi \times 50 MHz} = \underline{\underline{3.18 pF}}$$

$$\text{From Eqn. (7.206)}$$

$$f_z = \frac{G_{m2}}{2\pi C_c}$$

$$G_{m2} = g_{m6} = 3 mA/V$$

CON

$$f_z = \frac{3 \text{ mA/V}}{2\pi \times 3.18 \text{ pF}} = \underline{\underline{150.14 \text{ MHz}}}$$

From Eqn. (7.210)

$$f_{p2} = \frac{G_{m2}}{2\pi C_2} = \frac{3 \text{ mA/V}}{2\pi \times 3 \text{ pF}} = \underline{\underline{160 \text{ MHz}}}$$

7.95

$$(a) \underline{I_{E1} = I_{E2} = 0.1 \text{ mA} \approx I_{E3}, I_{E4}}$$

$$\underline{I_{E5} \approx 1 \text{ mA}} \text{ and since the output is held at 0V}$$

$$\underline{I_{E6} = 2 \text{ mA}}$$

$$(b) r_{e1} = r_{e2} = \frac{25 \text{ mV}}{0.1 \text{ mA}} = 250 \Omega$$

$$r_{e5} = \frac{25 \text{ mV}}{1 \text{ mA}} = 25 \Omega$$

$$r_{e6} = \frac{25 \text{ mV}}{2 \text{ mA}} = 12.5 \Omega$$

For the active loaded differential pair; Recall from Eqn.

$$(7.161) \quad G_{m1} = g_{m1} \approx \frac{1}{r_{e1}} = \frac{1}{250} = 4 \frac{\text{mA}}{\text{V}}$$

$$R_{o1} = (\beta + 1) r_{e5} \text{ Since all } r_{o}'s = \infty$$

$$R_{o1} = 101 \times 25 = 2525 \Omega$$

$$\Rightarrow A_1 = G_{m1} R_{o1} = 4 \frac{\text{mA}}{\text{V}} \times 2525 \Omega = \underline{\underline{10.1 \text{ V/V}}}$$

For the common-emitter:

$$A_5 = -g_{m5} R_{cs}$$

$$\approx -\frac{\beta R_L}{r_{e5}} = -\frac{100 \times 10 \text{ K}}{25}$$

$$= -40,000 \text{ V/V}$$

For the emitter follower:

$$A_6 \approx 1$$

$$A_{2nd-stage} = A_5 \cdot A_6 = -40,000 \text{ V/V}$$

$$A = A_1 \cdot A_{2nd-stage} = 10.1 \times -40,000 = \underline{\underline{-404,000 \text{ V/V}}}$$

(c) Since the dominant low-frequency pole is set by C_c & f_{p3}

$$f_p = \frac{1}{2\pi R_{o1} (A_5 + 1) C_c} = 100 \text{ Hz}$$

$$\Rightarrow C \approx \frac{1}{(2\pi \times 2525 \times 40 \text{ K} \times 100)} \text{ by Miller effect}$$

$$= \underline{\underline{15.76 \text{ pF}}}$$

7.96

$$I_B = 225 \mu\text{A}$$

$$\mu_n C_{ox} = 180 \mu\text{A/V}^2$$

$$\mu_p C_{ox} = 60 \mu\text{A/V}^2$$

$$\text{For } Q_8 \text{ \& } Q_9: W/L = 60/0.5$$

$$\Rightarrow |V_{ov}| = \sqrt{\frac{2I_D}{K_p'(W/L)}}$$

$$|V_{ov}|_{8,9} = \sqrt{\frac{2 \times 225 \mu}{60 \mu \times 120}} = 0.25 \text{ V}$$

$$\text{then } g_{m8,9} = \frac{2I_D}{|V_{ov}|} = \frac{2 \times 225 \mu}{0.25 \text{ V}} = 1.8 \text{ mA/V}$$

Since g_m of Q_{10} , Q_{11} & Q_{13} are identical to g_m of Q_8 & Q_9

$$\text{then } V_{ov,13} = 0.25 \text{ V}$$

Thus for Q_{13}

$$(0.25)^2 = \frac{2 \times 225 \mu}{180 \mu \times (W/L)_{13}}$$

$$\Rightarrow (W/L)_{13} = 40 \text{ i.e. } (20/0.5)$$

Since Q_{12} is 4 times as wide as Q_{13} , then

CONT.

$$(W/L)_{12} = \frac{4 \times 20}{0.5} = 80/0.5$$

$$R_B = \frac{2}{\sqrt{2 K_n' (W/L)_{12} I_B}} \cdot \left(\sqrt{\frac{(W/L)_{12}}{(W/L)_{13}}} - 1 \right)$$

$$= \frac{2}{\sqrt{2 \times 180 \mu \times \frac{80}{0.5} \times 225 \mu}} \cdot \left(\sqrt{\frac{80/0.5}{20/0.5}} - 1 \right)$$

$$\rightarrow R_B = \underline{555.6 \mu}$$

The voltage drop on R_B is:
 $555.8 \times 225 \mu = \underline{0.125 V}$.

To obtain the gate voltages:
 (assume $|V_{th}|, |V_{tp}| = 0.7 V$)

$$V_{OV12} = \sqrt{\frac{2 \times 225 \mu}{180 \mu \times \frac{80}{0.5}}} = 0.125 V$$

$$V_{OV12} = V_{GS12} - V_{th}$$

$$\rightarrow V_{GS12} = 0.125 + 0.7 = 0.825 V$$

thus,

$$V_{G12,13} = V_{GS12} + I_B R_B - V_{SS}$$

$$= 0.825 + 0.125 - 1.5$$

$$= \underline{-0.55 V}$$

$$V_{OV11} = |V_{OV8}| = 0.25 V$$

$$\Rightarrow V_{GS11} = 0.25 + 0.7 = 0.95 V$$

$$V_{G11} = -0.55 + 0.95$$

$$V_{G11} = V_{G10} = \underline{0.4 V}$$

$$V_{G8} = V_{DD} - V_{SG8} = 1.5 + (-0.25 - 0.7)$$

$$= \underline{+0.55 V}$$

Finally, from the results above:

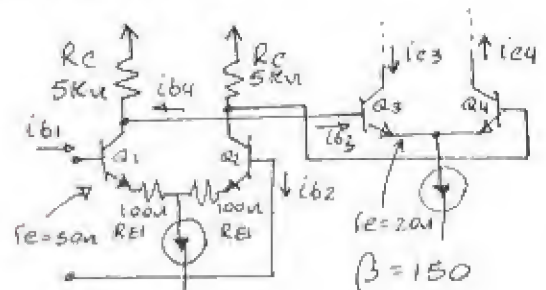
$$(W/L)_{10} = 20/0.5$$

$$(W/L)_{11} = 20/0.5$$

$$(W/L)_{12} = 80/0.5$$

$$(W/L)_{13} = 20/0.5$$

7.97



$$A_1 = \frac{2 R_C \parallel R_{id2}}{2 (R_{E1} + r_{e1})}$$

$$R_{id2} = (\beta + 1) (2 r_{e2}) = 6.04 K\Omega$$

$$\Rightarrow A_1 = \underline{12.5 V/V}$$

$$A_i = \frac{i_{e4}}{i_{b1}} = \beta_1 \cdot \frac{2 R_C}{R_{id2} + 2 R_C} \beta_4$$

$$= 1.4 \times 10^4 \underline{A/A}$$

7.98

$$R_{id1} = (\beta + 1) (R_{E1} + r_{e1}) 2$$

$$= 101 \times (100 + 100) 2 = \underline{40.4 K\Omega}$$

increase!

$$R_{id2} = (\beta + 1) (2) (R_{E2} + r_{e2})$$

$$= 101 \times (25 + 25) 2 = 10.1 K\Omega$$

$$\therefore A_1 = \frac{2 (20 K) \parallel R_{id2}}{2 (R_{E1} + r_{e1})} = \underline{20.2 V/V}$$

decrease

$$A_2 = -\frac{R_3 \parallel R_{id3}}{2 (R_{E2} + r_{e2})} = -29.6 V/V$$

observe that A_3 and A_4 are unchanged.

$$A = A_1 A_2 A_3 A_4$$

$$= (20.2) (29.6) (6.42) (0.998)$$

$$= \underline{3823 V/V}$$

decrease.

7.99

$$R_o \approx \frac{R_s + r_{e8}}{\beta + 1} = R_{c1}'$$

CONT.

Thus R_5 affects R_o

We want $R_o' \parallel 3K = 76$

$$\Rightarrow R_o' = 78\Omega$$

$$\Rightarrow R_5 = (78 - r_{e8})(\beta + 1) = 7.37K\Omega$$

$$A_3 = -\frac{R_5 \parallel R_{i4}}{r_{e4} + R_4}; R_{i4} \approx 304K\Omega$$

$$\text{and } A_3 = -3.09 \text{ V/V}$$

$$\text{and } A = 8513 \cdot \frac{3.09}{6.42} = 4104 \text{ V/V}$$

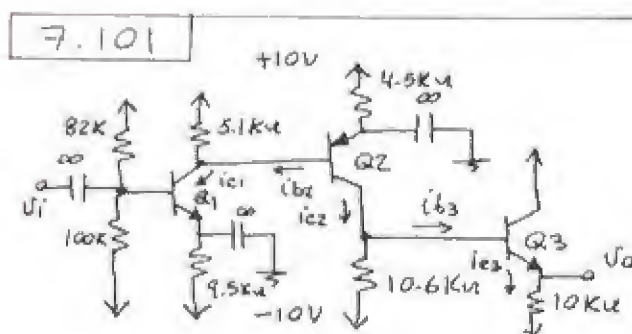
The gain has been reduced by a factor of 2.09 and can be restored by reducing R_4 by this same factor to increase A_3 . Thus $R_4 = 1.1K\Omega$ (Note that this is a first order approximation).

Thus,

$$A_{LOAD} = \frac{A \cdot R_L}{R_L + R_o} = \frac{173.1 \times 10^3 \cdot 100}{100 + 3000} = 5583 \text{ V/V}$$

For the original amplifier:

$$A_{LOAD} = 8513 \times \frac{100}{100 + 152} = 3378 \text{ V/V}$$



$$(a) I_{E1} = \frac{20V \times 100K}{82K + 100K} - 0.7 = \frac{9.5K + (82K \parallel 100K)}{\beta + 1}$$

$$\beta = 100 \Rightarrow I_{E1} = 1.03mA$$

$$\alpha = \frac{100}{101} \Rightarrow I_{C1} = 1.02mA$$

$$V_{C1} \approx 10V - 1.02mA \times 5.1K\Omega = 4.8V$$

$$I_{E2} = \frac{(10 - 0.7 - 4.8)V}{4.5K\Omega} = 1mA$$

$$\rightarrow I_{C2} = 0.99mA$$

$$V_{C2} \approx 0.99mA \times 10.6K\Omega - 10 = 0.5V$$

$$\Rightarrow V_{DCC} = 0.5 - 0.7 = -0.2V$$

$$I_{E3} = \frac{-0.2 - (-10)}{10K} = 0.98mA$$

$$\rightarrow I_{C3} = 0.97mA$$

Thus all transistors are operating at $I_C \approx 1mA$

CONT.

7.100

$$(a) A_3 = -\frac{R_{i4}}{2.325K\Omega} = -\frac{303.5}{2.325} = -130.5 \text{ V/V}$$

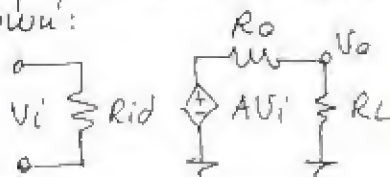
$$\text{i.e. } A_3 \text{ is increased by } \frac{130.5}{6.42} = 20.33$$

$$\Rightarrow A = 8513 \times 20.33 = 173.1 \times 10^3 \text{ V/V}$$

(b) Let the output resistance of the current source be $R \rightarrow \infty$
 $R_o = 3K \parallel \left(\frac{R}{\beta + 1} + r_e \right)$

$$= 3K$$

The amplifier can be modelled as shown:



$$(b) R_{in} = 82K \parallel 100K \parallel r_{\pi 1}$$

where $r_{\pi 1} = \frac{\beta}{g_{m1}} = \frac{100}{40m} = 2.5K\Omega$

$$\Rightarrow R_{in} = (82 \parallel 100 \parallel 2.5)K = \underline{\underline{2.37K\Omega}}$$

$$R_{out} = 10K \parallel \left[r_{e3} + \frac{10.6K}{\beta+1} \right]$$

$$= 10K \parallel \left[25 + \frac{10.6K}{101} \right]$$

$$= \underline{\underline{128\Omega}}$$

$$(c) \frac{i_{c1}}{v_i} = g_{m1} = 40mA/V$$

$$\frac{i_{b2}}{i_{c1}} = \frac{5.1K}{5.1K + r_{\pi 2}} = \frac{5.1}{5.1 + 2.5} = 0.671 \frac{A}{A}$$

$$\frac{i_{c2}}{i_{b2}} = \beta_2 = 100 \frac{A}{A}$$

$$\frac{i_{b3}}{i_{c2}} = \frac{10.6K}{10.6K + (\beta+1)(r_{e3} + 10K)} = 0.01036 \frac{A}{A}$$

$$\frac{i_{e3}}{i_{b3}} = \beta_3 + 1 = 101$$

$$v_o = i_{e3} \times 10K$$

Thus,

$$\frac{v_o}{v_i} = \frac{10 \times 101 \times 0.01036 \times 100 \times 0.671}{40}$$

$$= \underline{\underline{2.81 \times 10^4 V/V}}$$

$$(d) f_{p2} = 1 / (2\pi C_2 \cdot R_2)$$

where: $R_2 = 5.1K \parallel r_{\pi 2}$

$$= 5.1K \parallel 2.5K = 1.68K\Omega$$

$$C_2 = C_{\pi 2} + C_{\mu 2} (1 + g_{m2} R_{L2})$$

with:

$$R_{L2} = 10.6K \parallel (\beta+1)(r_{e3} + 10K)$$

$$= 10.6K \parallel 101 \times (25 + 10K)$$

$$= 10.5K\Omega$$

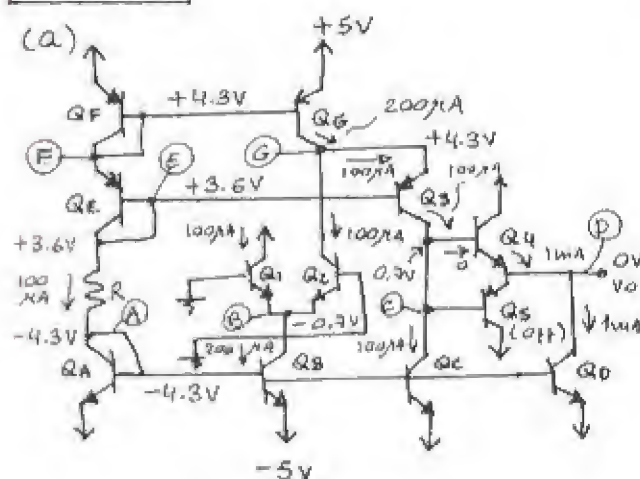
$$\Rightarrow C_2 = 10p + 2p (1 + 40m \times 10.5K)$$

$$= 852pF$$

$$\Rightarrow f_{p2} = \frac{1}{2\pi \times 852p \times 10.5K}$$

$$= \underline{\underline{17.8KHz}}$$

7.102



DC Analysis

$$R = \frac{3.6 - (-4.3)}{100\mu A} = \underline{\underline{79K\Omega}}$$

Node voltages:

$$V_A = -4.3V, \quad V_B = -0.7V$$

$$V_C = +0.7V, \quad V_D = 0V$$

$$V_E = +3.6V, \quad V_F = +4.3V$$

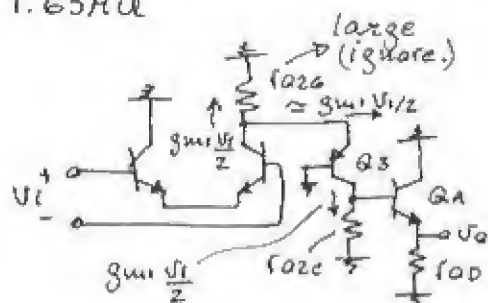
$$V_G = +4.3V$$

(b)

Transistor	I_c (mA)	g_m (mA/V)	r_o (M Ω)
Q1	0.1	4	2
Q2	0.1	4	2
Q3	0.1	4	2
Q4	1.0	40	0.2
Q5	0	0	∞
Q6	0.1		
Q7	0.2		
Q8	0.1	2
Q9	1.0	0.2
Q10	0.1		
Q11	0.1		
Q12	0.2	1 CONT.

(c) Total resistance at collector Q3 is

$$\begin{aligned} &\approx \beta_3 r_{03} \parallel r_{0c} \parallel (\beta_4 + 1) (r_{04} \parallel r_{0p}) \\ &= 100 \times 2 \parallel 2 \parallel 101 (0.2 \parallel 0.2) \\ &= 1.65 \text{ k}\Omega \end{aligned}$$



$$\frac{U_{c3}}{U_1} = + g_{m1} \times \frac{1}{2} \times 1.65 \times 10^3 = 3300 \frac{V}{V}$$

$$\frac{U_0}{U_{c3}} \approx 1$$

Thus, $\frac{S_o}{V_i} \approx \underline{\underline{3300 \text{ V/V}}}$ (polarity correct)

(d) $R_{in} = 2 \Omega$
 $= 2 \times \frac{100}{4} = \underline{\underline{50 \text{ k}\Omega}}$

$$R_{out} = r_{o4} \parallel r_{o4} \parallel \left[r_{e4} + \frac{r_{o2c} \parallel \beta_3 r_{o3}}{\beta + 1} \right]$$

$$= 0.2 \parallel 0.2 \parallel \left[25.1 \bar{0}^6 + \frac{2 \parallel 100 \times 2}{101} \right]$$

$$\approx \underline{16.4 \text{ K}\Omega}$$

$$\begin{aligned} (e) \quad V_{IcH} |_{\min} &= -4.3 - 0.4 + 0.7 \\ &= \underline{\underline{-4V}} \\ V_{IcH} |_{\max} &= V_G + 0.4 = + \underline{\underline{4.7V}} \end{aligned}$$

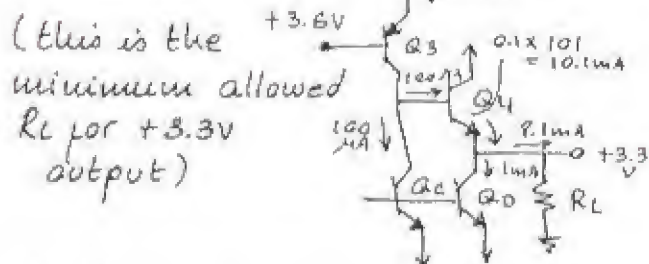
(f) The voltage at the base of Q_4 can rise to V_{B3} :
 $(V_E) + 0.4 = +4V$
 before Q_3 saturating. Thus V_D can go up to +3.3V

The voltage at the output can go down to $V_{\text{base}} \text{ of } Q_2 + 0.4$
 $= V_A - 0.4 = -4.3 - 0.4 = -4.7\text{V}$

Thus the linear range at the output is -4.7V to +3.3V

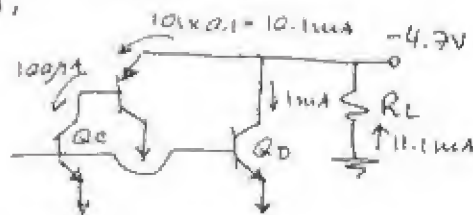
(g) At the positive limit of V_o , i.e. $V_o = +3.3V$ and Q_2 just cutoff

$$R_L = \frac{3.3V}{9.1mA} = 363\Omega$$



At the negative limit of V_0 , i.e. $V_0 = -3.3V$ and Q_1 has cut-off. Q_3 will also be cut-off, and Q_4 will cut-off.

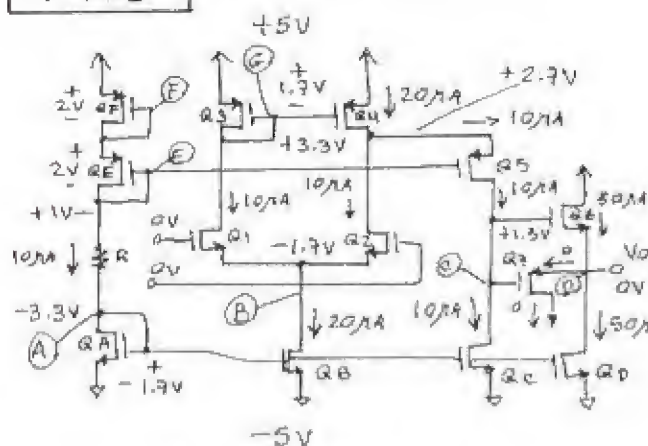
Thus,



$$R_L = \frac{4.7}{11.1 \text{ mA}} = \underline{\underline{423 \Omega}}$$

This is the minimum allowed R_L for a $-4.7V$ output.

7.103



DC analysis.

$$(a) I_{REF} = 10\mu A = \frac{1}{2} \times 40 \times \frac{5}{5} (V_{GS1} - V_t)^2$$

$$\Rightarrow V_{GS1} = 1.71V \approx 1.7V$$

$$10 = \frac{1}{2} \times 20 \times \frac{5}{5} (V_{GS1,F} - 1)^2$$

$$\Rightarrow V_{GS1,F} = 2V$$

$$R = \frac{3 - (-3.3)}{10\mu A} = \underline{660K\Omega}$$

(b) See figure above

$$V_{GS1} = V_{GS2} = V_{GS3} \approx 1.7V$$

$$V_{GS3} = \sqrt{\frac{2 \times 10}{20 \times \frac{5}{5}}} + 1 = 1.71V \approx 1.7V$$

$$V_{GS5} = V_{GS3} = 1.7V$$

$$\text{For } Q_6: 50 = \frac{1}{2} \times 40 \times \frac{50}{5} (V_{GS6} - V_t)^2$$

$$\Rightarrow V_{GS6} = 1.50V$$

$$V_A = -3.3V \quad V_B = -1.7V$$

$$V_C = +1.5V \quad V_D = 0V$$

$$V_E = +1V \quad V_F = +3V$$

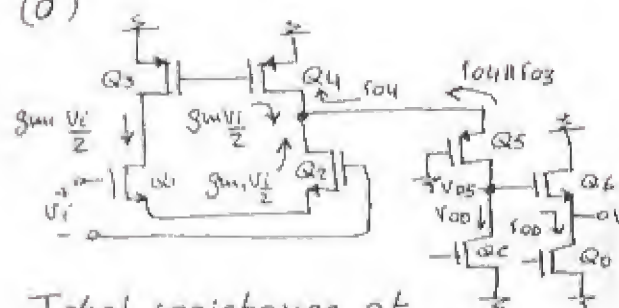
$$V_G = +3.3V \quad V_H = +2.7V$$

(c) Transistor	I_D (μA)	V_{GS} (V)	g_m (mA/V)	r_o (M Ω)
Q_1	10	1.7	28.3	5
Q_2	10	1.7	28.3	5
Q_3	10	1.7	28.3	5
Q_4	20	1.7	56.6	2.5

Q_5	10	1.7	28.3	5
Q_6	50	1.5	200	1
Q_7	0	-1.5	0	∞
Q_A	10	1.7	28.3	5
Q_B	20	1.7	56.6	2.5
Q_C	10	1.7	28.3	5
Q_D	50	1.7	141.4	1
Q_E	10	2	20	5
Q_F	10	2	20	5

(*) cut-off.

(d)



Total resistance at the drain of Q_5 , R , is:

$$R = (g_{m5} r_{o5}) (r_{o4} \parallel r_{o2}) \parallel r_{o6}$$

$$= [(28.3 \times 5) (2.5 \parallel 2)] \parallel 5$$

$$= 4.9K\Omega$$

$$\text{Thus, } \frac{V_o}{V_i} = g_{m1} R$$

$$= 28.3 \times 4.9 = 138.7 \text{ V/V}$$

$$\text{and } \frac{V_o}{V_i} = \frac{(r_{o4} \parallel r_{o6})}{V_{GS} (r_{o4} \parallel r_{o6}) + \frac{1}{g_{m6}}}$$

$$= \frac{(1 \parallel 1)}{(1 \parallel 1) + \frac{1}{200}} \approx 1$$

$$\frac{V_o}{V_i} = 138.7 \text{ V/V}$$

$$R_{in} = \infty$$

$$R_{out} = r_{o4} \parallel r_{o6} \parallel 1/g_{m6}$$

$$= 1 \parallel 1 \parallel 1/200 \text{ M}\Omega$$

$$\approx \underline{5K\Omega}$$

CONT.

$$(e) V_{Icm} |_{max} = V_G + V_E$$

$$= +4.3V$$

$$V_{Icm} |_{min} = V_{G1} + V_{Bmin}$$

$$= V_{G1} + V_A - V_E$$

$$= 1.7 - 3.3 - 1 = -2.6V$$

$$\Rightarrow \hat{V}_O = 1.45V$$

That is, the range of V_O is $-1.45V$ to $0.17V$

$$(f) V_{Omax} = V_{Cmax} - V_{GS6}$$

$$= V_E + |V_E| - V_{GS6}$$

$$= +1 + 1 - 1.5 = +0.5V$$

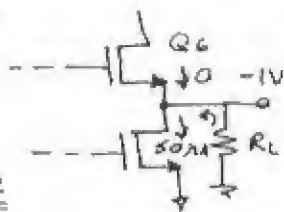
$$V_{Omin} = V_A - V_E = -3.3 - 1 = -4.3V$$

(g) Q_6 cuts off

thus,

$$\frac{1V}{R_L} = 50\mu A$$

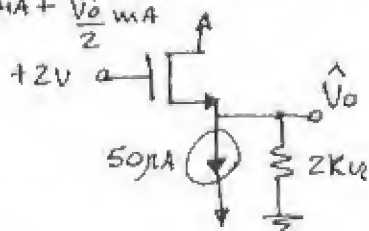
$$R_L = \frac{1V}{50\mu A} = 20K\Omega$$



(h) Maximum possible voltage at drain of Q_5 is $+2V$.

At this value we have:

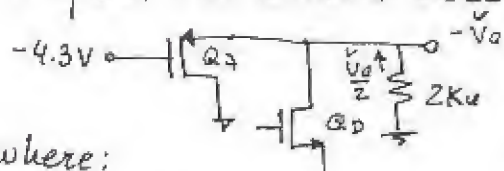
$$I_D = 50\mu A + \frac{\hat{V}_O}{2} mA$$



$$I_D = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (2 - \hat{V}_O - V_E)^2$$

$$\Rightarrow \hat{V}_O \approx 0.17V$$

For the lowest possible output, the circuit becomes



where:

Q_6 cuts off and Q_7 conducts

$$I_D = \frac{V_O}{2} - 0.05mA$$

$$= \frac{1}{2} \mu_p C_{ox} \left(\frac{100}{5} \right) (-\hat{V}_O + 4.3 - 1)^2$$

Chapter 8 - Problems

B.1

$$A_f = \frac{A}{1+A\beta} = 100$$

$$A\beta = \frac{10^5}{100} - 1 = 999$$

$$\Rightarrow \beta = \frac{999}{10^5} = 9.99 \times 10^{-3}$$

$$A = 10^3, \quad A_f = \frac{10^3}{1+10^3(9.99 \times 10^{-3})}$$

$$= 90.99$$

$$\frac{\Delta A_f}{A_f} = \frac{90.99 - 100}{100} \Rightarrow -9\%$$

B.2

(b) $A_f = 10 = \frac{100}{1+100\beta} \Rightarrow \beta = 90 \times 10^{-3}$

$$\beta = \frac{R_2}{R_1 + R_2} \Rightarrow \frac{R_2}{R_1} = \frac{1}{\beta} - 1 = 10.11$$

(c) amount of feedback $= 1 + A\beta$
 $= 1 + 100(90 \times 10^{-3}) = 10 \equiv 20 \text{ dB}$

(d) $V_o = 10V_s = 10V$
 $V_f = \beta V_o = 90 \times 10^{-3} \times 10 = 0.9V$
 $V_i = V_s - V_f = 1 - 0.9 = 0.1V$

(e) $A_f = \frac{80}{1+80(90 \times 10^{-3})} = 9.756$

$$\frac{\Delta A_f}{A_f} = \frac{9.756 - 10}{10} \Rightarrow -2.44\%$$

B.3

(b) $A_f = 10^3 = 10^3 / (1 + 10^3 \beta)$
 $\Rightarrow \beta = 900 \times 10^{-6}$
 $\frac{R_2}{R_1} = \frac{1}{\beta} - 1 = 1110$

(c) $1 + A\beta = 1 + 10^3(900 \times 10^{-6}) = 10 \equiv 20 \text{ dB}$

(d) $V_s = 0.01V$
 $V_o = 10^3 V_s = 10V$
 $V_f = \beta V_o = 900 \times 10^{-6} \times 10 = 9 \text{ mV}$

$$V_i = V_s - V_f = 1 \text{ mV}$$

(e) $A = 8000$

$$A_f = \frac{8000}{1+8000(900 \times 10^{-6})} = 975.6$$

$$\frac{\Delta A_f}{A_f} = \frac{975.6 - 1000}{1000} \equiv -2.44\%$$

B.4

All output voltage is fed back $\therefore \beta = 1$

$$A_f = \frac{100}{1+100 \times 1} = 0.99$$

$$1 + A\beta = 1 + 100 \times 1 = 101 \equiv 40.1 \text{ dB}$$

$$V_o = 0.99 V_s = 0.99V$$

$$V_i = V_s - V_o \beta = 1 - 0.99 = 10 \text{ mV}$$

$$A = 90 \Rightarrow A_f = \frac{90}{1+90 \times 1} \approx 0.989$$

$$\frac{\Delta A_f}{A_f} = \frac{0.989 - 0.99}{0.99} \equiv -0.1\%$$

B.5

$$V_s = 1V, \quad V_i = 10 \text{ mV}, \quad V_o = 10V$$

$$A_o = (V_o / V_i) = 10V / 10 \text{ mV} = 1000$$

$$V_i = V_s - V_f = V_s - \beta V_o = 1 - \beta 10$$

$$\Rightarrow \beta = (1 - 10^{-2}) / 10 = 0.999$$

B.6

$$A_f = \frac{A_o}{1+A_o\beta} = \frac{1}{1/A_o + \beta} = \frac{1}{\beta(1+1/A_o\beta)}$$

so $A_f + 1/\beta$ will be within $x\%$ when
 $1/(A_o\beta) = 0.01 \times x$

(a) For 1%: $A_o\beta = 1/0.01 = 100$

Many possible solutions.

Let $A_o = 10^5 \times A_o\beta = 100 \Rightarrow \beta = 10^{-3}$

(b) For 5%: $A_o\beta = 1/0.05 = 20$

Let $A_o = 10^5 \times A_o\beta = 20 \Rightarrow \beta = 2 \times 10^{-4}$

(c) For 10%: $A_o\beta = 1/0.1 = 10$

Let $A_o = 10^5 \times A_o\beta = 10 \Rightarrow \beta = 10^{-4}$

(d) For 50%: $A_o\beta = 1/0.5 = 2$

Let $A_o = 10^5$; $A_o \beta = 2 \Rightarrow \beta = 2 \times 10^{-5}$

% error	A_o	$A_o \beta$	$1 + A_o \beta$
1	10^5	100	101
5	10^5	20	21
10	10^5	10	11
50	10^5	2	3

8.7.

$0 \leq \beta \leq 1$ Linear

(a) For $A_o = 1$: $A_{f1} = \frac{A_o}{1 + A_o \beta} = \frac{1}{1 + 0} = 1 \text{ V/V}$

$A_{f2} = \frac{1}{1 + 1 \times 0.5} = 0.667 \text{ V/V}$

$A_{f3} = \frac{1}{1 + 1 \times 1} = 0.5 \text{ V/V}$

(b) For $A_o = 10$: $A_{f1} = \frac{10}{1 + 0} = 10 \text{ V/V}$

$A_{f2} = \frac{10}{1 + 10 \times \frac{1}{2}} = 1.6 \text{ V/V}$

$A_{f3} = \frac{10}{1 + 10 \times 1} = 0.909 \text{ V/V}$

(c) For $A_o = 100$: $A_{f1} = \frac{100}{1 + 0} = 100 \text{ V/V}$

$A_{f2} = \frac{100}{1 + 100 \times \frac{1}{2}} = 1.96 \text{ V/V}$

$A_{f3} = \frac{100}{1 + 100} = 0.99 \text{ V/V}$

(d) For $A_o = 10^4$: $A_{f1} = \frac{10^4}{1 + 0} = 10^4 \text{ V/V}$

$A_{f2} = \frac{10^4}{1 + 10^4 \times \frac{1}{2}} = 1.99 \text{ V/V}$

$A_{f3} = \frac{10^4}{1 + 10^4} = 0.9999 \text{ V/V}$

8.8

$A_o: 2 \text{ mV} \rightarrow 10 \text{ V}$

$A_\beta = 10 \text{ V} / (2 \times 10^{-3} \text{ V}) = 5000 \approx 74 \text{ dB}$

$A_F: 200 \text{ mV} \rightarrow 10 \text{ V}$

$A_F = (10^4 / 200) = 500 \approx 54 \text{ dB}$

$A_F = \frac{A_o}{1 + \beta A_o} = \frac{5000}{1 + 5000 \beta} = 500$

$\Rightarrow 1 + 5000 \beta = 10$

$\Rightarrow \beta = 9/5000 = 0.0018 \approx -54 \text{ dB}$

$(1 + A_o \beta) = 10 \approx 20 \text{ dB}$

$A_o \beta = 5000 (9/5000) = 9 \approx 19.08 \text{ dB}$

8.9

$\frac{dA_f}{A_f} = \frac{1}{1 + A\beta} \cdot \frac{dA}{A}$

$\frac{dA_f/A_f}{dA/A} = \frac{1}{1 + A\beta} \approx -20 \text{ dB}$

$\Rightarrow 1 + A\beta = +20 \text{ dB} \approx 10$

$\therefore A\beta = 9$

Require $\frac{1}{1 + A\beta} = \frac{1}{2} \Rightarrow A\beta = 1$

8.10

$A_o \approx 1000 \pm 30\%$ want $A_f = 100 \pm 1\%$

To reduce % change in A_o we need

$\frac{1}{1 + A\beta} \approx \frac{1}{30} \Rightarrow A_f = \frac{1000}{30} < 100$

For single stage $A_F = \frac{A}{1 + A\beta} \Rightarrow \frac{1}{1 + A\beta} = \frac{100}{1000} = \frac{1}{10}$

For two stages $A_2 = \frac{A}{1 + A\beta_2} \approx 10$
(identical)

$\Rightarrow (1 + A\beta_2) = 1000/10 = 100$

Thus each stage has $\pm 30/100 \% = \pm 0.3\%$

But two such stages may give $\pm 0.6\%$ OK

[3 stages $A_3 = A^{1/3} = 100^{1/3}$
 $(1 + A_o \beta_3) = 1000/100^{1/3} = 215$

Now each stage has $\pm 0.14\%$]

8.11

Gain desensitivity factor = $[1 + A_o \beta]$

$A_F = \frac{A_o}{1 + A_o \beta} = \frac{10^5}{1 + 10^5 \beta} = 10^3$

$$\Rightarrow \beta = 0.99 \times 10^{-3}$$

$$\text{From } \frac{dA_f}{A_f} = \frac{1}{1+A\beta} \cdot \frac{dA}{A}$$

(a) When A drops 10%

$$\text{then } A_f \text{ drops by } \frac{10\%}{1+A_0\beta} = \frac{10\%}{10^5/10^3} = 0.1\%$$

$$\text{But using } A_f = \frac{A}{1+A\beta} = \frac{0.9 \times 10^5}{1+(0.9 \times 10^5)(99/10^5)} = 998.89$$

$$\text{Corresponding \% } \frac{1000 - 998.89}{1000} = 0.11\% \quad (\text{close})$$

(b) When A drops 30%

$$\text{then } A_f \text{ drops by } \frac{30\%}{10^5} = 0.3\%$$

$$\text{while } A_f = \frac{0.7 \times 10^5}{1+(0.7 \times 10^5)(99/10^5)} = 995.7$$

$$\text{and } \frac{1000 - 995.7}{1000} = 0.43\% \quad (\text{not so close})$$

8.12

$$A(s) = A_m \frac{s}{s + \omega_L}$$

$$A_f(s) = \frac{A_m \frac{s}{s + \omega_L}}{1 + \frac{A_m s}{s + \omega_L} \beta} = \frac{A_m s}{s + \omega_L + A_m \beta s}$$

$$= \frac{A_m}{1 + A_m \beta} \cdot \frac{s}{s + \frac{\omega_L}{1 + A_m \beta}}$$

Thus

$$A_{mf} = \frac{A_m}{1 + A_m \beta}$$

$$\omega_{Lf} = \frac{\omega_L}{1 + A_m \beta}$$

Both decreased by same amount

8.13

$$\text{worst case: } A_{f1} = \frac{A_0}{1 + A_0 \beta} = 9.8 \quad (\text{dom 2\%})$$

$$\text{full battery: } A_{f2} = \frac{2A_0}{1 + 2A_0 \beta} = 10$$

$$\text{from } A_{f1}: 1 + A_0 \beta = A_0 / 9.8$$

$$\therefore \beta = \frac{1}{9.8} - \frac{1}{A_0}$$

$$\text{Then } A_{f2} = \frac{2A_0}{1 + 2A_0 \left[\frac{1}{9.8} - \frac{1}{A_0} \right]} = 10$$

$$\Rightarrow 1 + 2A_0 \left[\frac{1}{9.8} - \frac{1}{A_0} \right] = \frac{2A_0}{10}$$

$$\Rightarrow 2A_0 \left[\frac{1}{9.8} - \frac{1}{A_0} \right] = 2 - 1$$

$$\therefore 2A_0 = 9.8$$

$$\left[\text{Check } \frac{2A_0}{1 + 2A_0 \left[\frac{1}{9.8} - \frac{2}{2A_0} \right]} = 10 \right]$$

$$\frac{A_0}{1 + A_0 \left[\frac{1}{9.8} - \frac{1}{A_0} \right]} = 9.8 \quad \beta_{\text{const}}$$

8.14

$$A_f = \frac{A_0}{1 + A_0 \beta} = 10 = \frac{100}{1 + 100\beta}$$

$$\therefore (1 + A_0 \beta) = 100/10 = 10$$

$$f_L' = f_L / (1 + A_0 \beta) = 100/10 = 10 \text{ Hz}$$

$$f_H' = f_H (1 + A_0 \beta) = 10 \text{ K} \times 10 = 100 \text{ KHz}$$

8.15

Need pole at 0.5 MHz. any others should be well above for stability.

$$f_H = 10 \text{ KHz} \quad \text{and } f_{Hf} = 500 \text{ KHz}$$

$$\therefore \text{need } (1 + A\beta) = 500/10 = 50$$

$$\text{Thus } A_{f1} = \frac{A}{1 + A\beta} = \frac{1000}{50} = 20$$

$$\text{and } \beta = (50 - 1)/1000 = 4.9 \times 10^{-3}$$

Subsequent stages must provide gain

$$A_{\text{total}} / A_{f1} = 1000/20 = 50$$

$$\text{Let } f_{H2} = 3 \times f_{H1} = 3 \times 500 = 1500 \text{ KHz}$$

$$\text{needs } (1 + A\beta_2) = \frac{1500}{10} = 150$$

$$\text{Then } A_{f2} = \frac{1000}{150} = 6.67$$

$$\text{and } \beta_2 = \frac{150 - 1}{1000} = 0.149$$

This leaves stage 3 with $A_{f3} = \frac{50}{6.67} = 7.5$
 This gain needs $1 + A\beta = \frac{1000}{7.5} = 133.3$

$$\text{and } f_{Hf3} = 10k(1 + A\beta) = 1.33 \text{ MHz}$$

this is safely well above 500 kHz

$$\text{and } \beta_3 = 0.132$$

The actual f_{Hf} is given by

$$f_{Hf} = \frac{1}{\left[\left(\frac{1}{0.5}\right)^2 + \left(\frac{1}{1.5}\right)^2 + \left(\frac{1}{1.33}\right)^2\right]} \\ \approx 0.447 \text{ MHz close!}$$

Using a 4 stage amplifier would allow lower stage gains and higher f_{Hf} 's

8.16

$$V_o = V_s \frac{A_1 A_2}{1 + A_1 A_2 \beta} + V_N \frac{A_1}{1 + A_1 A_2 \beta}$$

$$\text{and } \frac{S}{N} = \frac{V_s}{V_N} A_2$$

if we raise V_s by factor A_2 then

S/N is improved by A_2 also

To reduce V_N from $\pm 1V$ to $\pm 1mV$ we must have $A_2 = 1000$, then

$$V_{os} = \frac{A_1 A_2}{1 + A_1 A_2 \beta} \leq \frac{1000 \times 0.9}{1 + 1000 \times 0.9 \beta} = 10 \\ \Rightarrow \beta = 0.99$$

$$\text{if } A_2 = 100; V_N = \pm 10mV$$

$$V_{os} = \frac{100 \times 0.9}{1 + 100 \times 0.9 \beta} = 10$$

$$\Rightarrow \beta = 0.089$$

$$\text{if } A_2 = 10; V_N = \pm 100mV$$

$$A_1 A_2 = 0.9 \times 10 \Rightarrow V_o = 9V < 10V!!$$

8.17

$$A_F = \frac{A_o}{1 + A_o \beta}$$

$$\frac{\Delta A_F / A_F}{\Delta A_o / A_o} = \frac{1}{1 + A_o \beta}$$

Then for 1% change in A_F for 90% change in A_o

$$1 + A_o \beta = 90 \Rightarrow A_o \beta = 89$$

$$\text{Then } A_F = 100 = \frac{A_o}{90} \Rightarrow A_o = 9000$$

Let $A_o \rightarrow 10 \times A_o$ then for $\beta = 89/A_o$

$$A_F = \frac{9000 \times 10}{1 + (9000 \times 10)(89/9000)} = 101.12$$

Therefore, select $A_o \geq 9 \times 10^4$

$$\text{and } \beta = 89/A_o$$

if $A_o \rightarrow 100 A_o$ + same β .

$$A_F = \frac{9000 \times 100}{1 + (9000 \times 100)(89/9000)} \\ \approx \frac{9000 \times 100}{8900} \\ \approx 101.12$$

if $A_o \rightarrow \infty$

$$A_F \Rightarrow A_o / (A_o \beta) \Rightarrow 1/\beta \\ \approx 9000/89 = 101.12$$

Ideally select A_o as high as possible

8.18

A_1 has f_{H1} high, A_2 has $A_m = 10V/V$
 with $f_L = 80Hz$, $f_H = 8kHz$.

$$A_F = \frac{A_1 A_2}{1 + A_1 A_2 \beta} = 100$$

Require $f_{Hf} = 40kHz = 8(1 + A_1 A_2 \beta)$

$$\therefore 1 + A_1 A_2 \beta = 40/8 = 5$$

$$\text{and } A_F = \frac{A_1 A_2}{5} = 100 \Rightarrow A_1 A_2 = 500$$

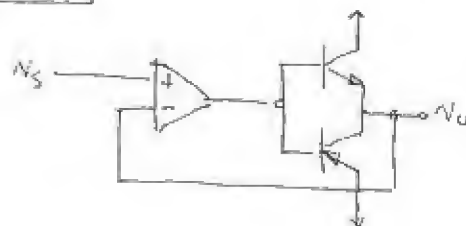
$$\Rightarrow A_1 = 500/A_2 = 500/10 = 50$$

$$1 + A_1 A_2 \beta = 5 \Rightarrow \beta = 4/A_1 A_2 = 4/500$$

$$\therefore \beta = 0.08$$

$$f_{Lf} = f_L / (1 + A_1 A_2 \beta) = 80/5 = 16Hz$$

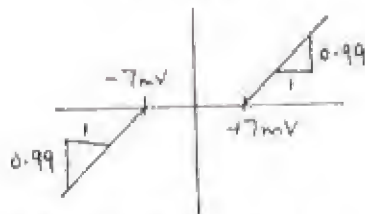
8.19



Dead band will be narrowed by the factor $1 + A\beta = 1 + A$ since $\beta = 1$ and since $A \gg 1$, $1 + A \rightarrow A$

\therefore new limits are $\pm \frac{0.7}{A} = \pm \frac{0.7}{100}$

$$= \pm 7 \text{ mV}$$



$$\text{New slope} \equiv \text{gain} = A_f = \frac{A}{1+A}$$

$$\Rightarrow \frac{100}{1+100} = 0.99$$

8.20

For $A = N_0/N_1 = 10^2$ (select lowest A_0)
to reduce % change in gain by factor of 10

$$1 + A\beta = 10 \Rightarrow \beta = 9/10^2$$

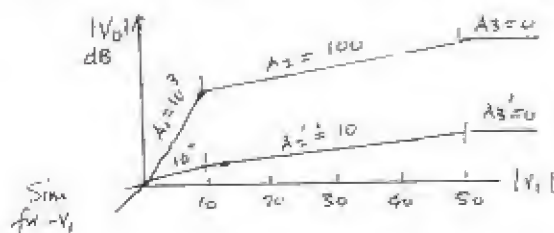
$$\text{For } A_2 = 10^2: A_{2F} = 10^3/10 = 10$$

$$\text{For } A_1 = 10^2: A_{1F} = \frac{A}{1+A\beta}$$

$$\therefore A_{2F} = \frac{10^3}{1+10^3(9/10^2)} = \frac{10^3}{91} = 10.98$$

For $A_3 = 0$: stays saturated

[For 10mV in and $A_1 = 10^3$, $V_0 = 10 \text{ V}$?]
[For 10mV in and $A_2 = 10^2$, $V_0 = 1 \text{ V}$]



8.21

$$V_S = 100 \text{ mV}, V_f = 95 \text{ mV}, V_0 = 10 \text{ V}$$

$$V_1 = V_S - V_f = 100 - 95 = 5 \text{ mV}$$

$$A_V = \frac{V_0}{V_1} = \frac{10 \text{ V}}{5 \text{ mV}} = 2 \times 10^3 \text{ V/V}$$

$$\beta = \frac{V_f}{V_0} = \frac{95 \times 10^{-3}}{10} = 9.5 \times 10^{-3} \text{ V/V}$$

8.22

$$I_S = 100 \mu\text{A}, I_F = 90 \mu\text{A}, I_0 = 10 \text{ mA}$$

$$A \equiv \frac{I_0}{I_S - I_F} = \frac{10 \times 10^{-3}}{(100 - 90) \times 10^{-6}} = 10^3 \text{ A/A}$$

$$= 1 \text{ mA}/\mu\text{A}$$

$$\beta \equiv \frac{I_F}{I_0} = \frac{90 \mu\text{A}}{10 \text{ mA}} = 9 \mu\text{A}/\text{mA}$$

8.23

For r_{o1}, r_{o2}, P_3 very large in Fig 8.5

At Q_1 : $I_S = I_F$ since $I_{Q1} = 0$

$$V_{G1} = [R_1 + R_2] I_S + I_0 R$$

$$V_{D1} = -g_{m1} V_{G1} R_{L1}$$

$$= -g_{m1} R_L [I_S(R_1 + R_2) + I_0 R_1]$$

$$I_0 = g_{m2} (V_{D1} - V_{S2})$$

$$= g_{m2} [(-g_{m1} R_L) [I_S(R_1 + R_2) + I_0 R_1] - I_0 R_1]$$

$$\therefore \frac{I_0}{I_S} = - \frac{g_{m2} [g_{m1} R_L (R_1 + R_2)]}{1 + g_{m2} g_{m1} R_L R_1 + g_{m2} R_1}$$

$$A_f = - \frac{R_1 + g_{m1} R_L (R_1 + R_2)}{R_1 + 1/g_{m2} + g_{m1} R_L R_1}$$

QED

$$R_{IN} \equiv \frac{V_S}{I_S} = I_S [R_1 + R_2] + I_0 R_1$$

$$I_S = I_S [R_1 + R_2 + A_f R_1]$$

$$\therefore R_{IN} = R_1 + R_2 + A_f R_1$$

QED

(b) When $g_{m1} R_{L1} = 100$, $R_L = 10 \text{ k}\Omega$, $R_2 = 90 \text{ k}\Omega$

and $g_{m2} = 5 \text{ mA/V}$

$$A_f = - \frac{R_1 + g_{m1} R_{L1} (R_1 + R_2)}{R_1 + 1/g_{m2} + g_{m1} R_L R_1}$$

$$= - \frac{10^4 + 100(100 \times 10^3)}{10^4 + 1000/5 + 100 \times 10^4}$$

$$= - 9.91 \text{ A/A} \approx -10 \text{ A/A}$$

$$\frac{I_o}{\tilde{I}_s} = \frac{\frac{\mu(R_2+r)}{R_L+r\parallel R_2}}{1 + \frac{\mu(R_2+r)}{R_L+r\parallel R_2} \cdot \frac{r}{r+R_2}}$$

$$\Rightarrow \frac{1}{\mu \gg 1} \frac{1}{r/(r+R_2)} \approx \frac{1}{\beta}$$

Section 8.4 The Series-Shunt Feedback Amplifier

8.27

$$A_F = \frac{A}{1+A\beta} = \frac{10^3 \times 2}{1+2 \cdot 10^3 \times 0.1} = 9.95 \text{ V}$$

$$R_{if} = R_i(1+A\beta) = 1(201) = 201 \text{ k}\Omega$$

$$R_{of} = R_o/(1+A\beta) = 1/201 = 4.975 \text{ k}\Omega$$

8.28

Here R_o is lowered by amount of feedback

$$\text{i.e. } (1+A\beta) = 80$$

$$\Rightarrow A\beta = 79$$

$$R_o = R_{of}(1+A\beta) = 100 \times 80 = 8 \text{ k}\Omega$$

8.29

$$A_o = 10^4 \text{ V/V} \quad f_t = 1 \text{ MHz}$$

$$20 \text{ dB/dec roll off} \therefore f_p = f_t/A_o = 100 \text{ Hz}$$

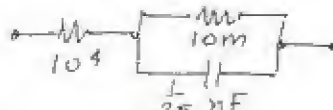
$$A(f) = \frac{A_o}{1+jf/f_p} = \frac{10^4}{1+jf/100}$$

$$\text{loop gain} = A(f)\beta = \frac{10^4(0.1)}{1+jf/100} = \frac{10^5}{jf+100}$$

$$Z_{if} = R_i(1+A\beta) = 10^4 \left(1 + \frac{10^3}{1+jf/100}\right)$$

$$= 10^4 + \frac{10^7}{1+jf/100} \approx R_A + \frac{R_B}{1+sR_B/C}$$

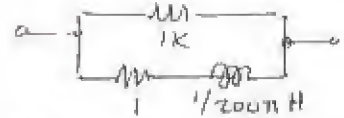
Thus



$$Z_{of} = \frac{R_o}{(1+A\beta)} = \frac{10^3}{1+10^3/(1+jf/100)}$$

$$\therefore Z_{of} = \frac{1}{\frac{1}{10^3} + \frac{1}{1+jf/100}}$$

$$= \frac{1}{\frac{1}{R_A} + \frac{1}{R_B + j\omega L}}$$



At $f=10^3$

$$|Z_{if}(10^3)| = \left| 10^4 + \frac{10^7}{1+j10^3/100} \right| = 1 \text{ M}\Omega$$

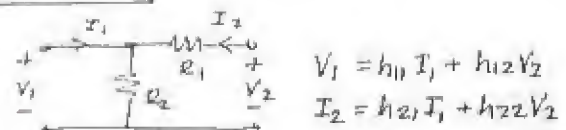
$$|Z_{of}(10^3)| = \left| \frac{1}{\frac{1}{10^3} + \frac{1}{1+j10^3/100}} \right| = 10 \Omega$$

At $f=10^5$

$$|Z_{if}(10^5)| = \left| 10^4 + \frac{10^7}{1+j10^5/100} \right| = 14.1 \text{ k}\Omega$$

$$|Z_{of}(10^5)| = \left| \frac{1}{\frac{1}{10^3} + \frac{1}{1+j10^5/100}} \right| = 700 \Omega$$

8.30



$$V_1 = h_{11}I_1 + h_{12}V_2$$

$$I_2 = h_{21}I_1 + h_{22}V_2$$

$$(a) \quad h_{11} = \left. \frac{V_1}{I_1} \right|_{V_2=0} = R_1 \parallel R_2 = \frac{R_1 R_2}{R_1 + R_2} \quad \Omega$$

$$h_{12} = \left. \frac{V_1}{V_2} \right|_{I_1=0} = \frac{R_2}{R_1 + R_2} \quad \text{V/V}$$

$$h_{21} = \left. \frac{I_2}{I_1} \right|_{V_2=0} = -\frac{R_2}{R_1 + R_2} \quad \text{A/A}$$

$$h_{22} = \left. \frac{I_2}{V_2} \right|_{I_1=0} = \frac{1}{R_1 + R_2} \quad \text{V}^{-1}$$

$$(b) \quad \beta = \left. \frac{V_1}{V_2} \right|_{I_2=0} = h_{12} = \frac{R_2}{R_1 + R_2}$$

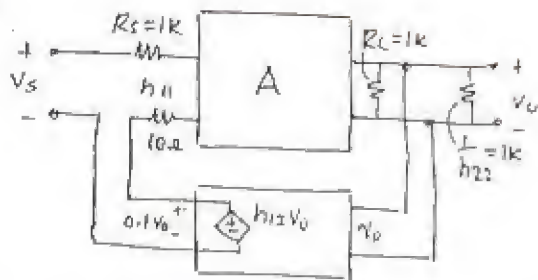
$$\Rightarrow \frac{R_1}{R_2} = \frac{1}{\beta} - 1 = 99$$

$$\Rightarrow R_2 = R_1/99 = 10.1 \Omega$$

$$\text{Thus } h_{11} = 10 \Omega; \quad h_{12} = 0.01 \text{ V/V}$$

$$h_{21} = -0.01 \text{ A/V}; \quad h_{22} = 0.99 \times 10^{-3}$$

(c)



8.31

$$R_{of} = \frac{R_o}{1+A\beta} = \frac{1000}{1+A\beta} = 100 \Omega$$

$$\Rightarrow 1+A\beta = 1000/100 = 10$$

$$\Rightarrow A_F = \frac{A}{1+A\beta} = \frac{100}{10} = 10 \text{ V/V}$$

$$\text{if } \beta = 1: R_{of} \Rightarrow \frac{R_o}{1+A} = \frac{1000}{1+10^4} = 9.9 \Omega$$

$$R_i = R_s + r_{e1} + \frac{(R_1 \parallel R_2)}{1+\beta}$$

$$= 100 + 250 + 909/101 = 700 \Omega$$

$$R_o = R_L \parallel (R_1 + R_2) \parallel (r_{e2} + r_{o1}/\beta + 1)$$

$$= 2k \parallel 10k \parallel \infty = 1.67 k\Omega$$

$$A = \frac{r_{o1} \parallel (\beta + 1)(r_{e3} + 10k \parallel 2k)}{R_s + r_{e1}} \times \frac{2k \parallel 10k}{2k \parallel 10k + r_{e3}}$$

$$\beta = \frac{R_1}{R_1 + R_2} = \frac{1}{1+10} = 0.0909 \text{ V/V}$$

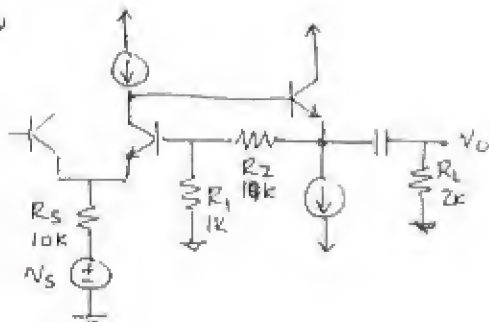
$$A_F = \frac{A}{1+A\beta} = \frac{16.4}{1+23.15 \times 0.0909} = \frac{1.67}{1.69} = 7.45 \text{ V/V}$$

$$R_{if} = R_{in}(1+A_F) = 700(3.1) = 2.17 k\Omega$$

Neglecting base currents since $\beta \gg 1$ DC voltage at input = $I_{B1}R_s = 0.01 \text{ V}$ DC voltage at output = 0 V

8.32

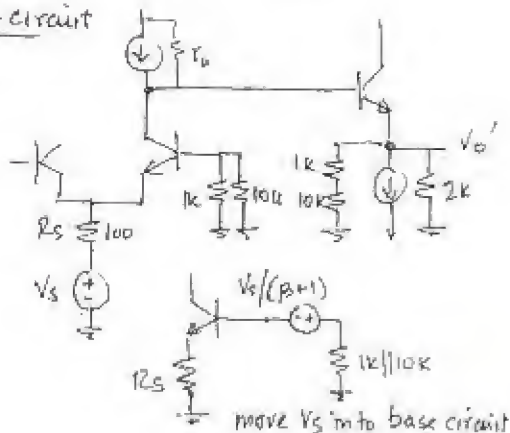
Redraw



$$r_{e1} = V_T/I_E = 25 \text{ mV}/0.1 \text{ mA} \approx 250 \Omega$$

$$r_{e2} = 25/1 = 25 \Omega$$

A-circuit

move V_s into base circuit

8.33

 $Q_3 + Q_4$ form current multiplier
 $\times 120/40 = \times 3$

$$g_{m1} = 2 \sqrt{\frac{1}{2} 120 (20/1) 100} \approx 693 \mu\text{A/V}$$

$$g_{m5} = 2 \sqrt{\frac{1}{2} 60 (20/1) 1000} \approx 1550 \mu\text{A/V}$$

$$g_{m3} = 2 \sqrt{\frac{1}{2} 60 (40/1) 100} \approx 693 \mu\text{A/V}$$

$$g_{m4} = 2 \sqrt{\frac{1}{2} 60 (120/1) 300} \approx 2078 \mu\text{A/V}$$

$$g_{m2} = g_{m1} = 693 \mu\text{A/V}$$

$$r_{o1} = 24/100 \Rightarrow 240 k\Omega$$

$$r_{o2} = 24/100 \Rightarrow 240 k\Omega$$

$$r_{o3} = 24/100 \Rightarrow 240 k\Omega$$

$$r_{o4} = 24/300 \Rightarrow 80 k\Omega$$

$$r_{o5} = 24/1000 \Rightarrow 24 k\Omega$$

(c) open-loop gain $A\beta \approx g_{m1}(r_{o1} \parallel r_{o3}) \times 1$

$$\left[\frac{(3 \times g_{m1})(r_{o4})}{3} \right] \approx g_{m1} r_{o1}$$

$$\beta = 1: \therefore A = g_{m1}(r_{o2} \parallel r_{o3})$$

$$\Rightarrow A \approx 693 \times 120 \times 10^{-3} = 84$$

$$(d) \quad A_F = \frac{A}{1+A_B} = \frac{84}{1+84} = 0.988 \text{ V/V}$$

$$R_o = r_{os} \parallel r_{os} = 12 \text{ k}$$

$$R_{of} = R_o / (1 + A\beta) = 12 / 85 = 140 \Omega$$

(e) To obtain $V_o/V_s = 5$ we could change direct connection from Q55 to Q26 by voltage divider $R_1/(R_1+R_2)$ to change β from 1 to $1/5.3$ then

$$A_F = \frac{84}{1 + 84 \times 1/5.3} = \frac{84}{16.8} = 5$$

Now $1 + A_\beta = 16.8$

$$R_{of}'' = R_o / (1 + \beta'' A_v) = 12 / 16.8 = 714 \Omega$$

8.34

Since $V_{G1} = 0 = V_{G2}$

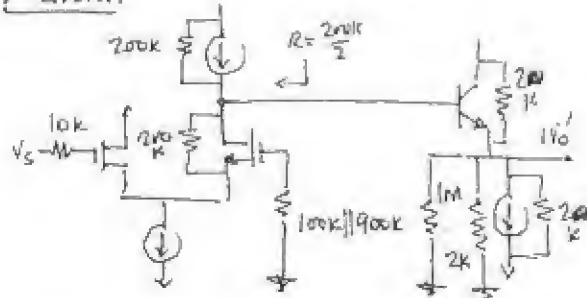
$$\Rightarrow V_{E3} = V_0 = 0 \text{ and } V_{B3} = +0.7V$$

$$g_{m1} = g_{m2} = 2 \sqrt{\frac{1}{2} K' (W/L) I} = 2 \sqrt{\frac{1}{2} (1) (0.5)} = 1 \text{ mA/V}$$

$$r_{e3} = V_T / I_{E3} = 5 \Omega$$

$$r_e = V_A / I = 100 / 0.5 = 200 \text{ k}$$

A - circuit



$$R_1 = \infty$$

$$R_u = 1\text{M} \parallel 2\text{k} \parallel \frac{20\text{k}}{1} \parallel \left(r_{e3} + \frac{20\text{k}}{\beta + 1} \right) = 622.2\Omega$$

$$A = \frac{100 \parallel (20 \parallel (r_{e3} + 10k) \parallel 10k \parallel 2k)}{2.9m} \times \frac{1.66k}{r_{e3} + 1.66k} = 31.3 V/V$$

$$\beta = \frac{100}{100 + 900} = 0.1 \text{ V/V}$$

$$A_F = \frac{A}{1 + A\beta} = \frac{31.3}{1 + 31.3 \times 0.1} = 7.58 \text{ V}$$

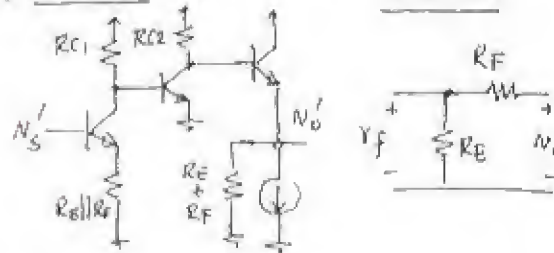
$$R_{if} = \infty \quad \therefore R_{in} = \infty$$

$$R_{of} = \frac{R_o}{1 + A\beta} = \frac{67.2 \Omega}{1 + 3.13} = 150.6 \Omega$$

$$R_{of} = R_{out} \parallel R_L \Rightarrow R_{out} = 163 \Omega$$

8. 4. 5

(a) A - circuit



B-circuit

(b) For $A\beta \gg 1$: $A_F = \frac{A}{1+A\beta} \Rightarrow \frac{1}{\beta}$

$$\beta = \frac{R_E}{R_E + R_F} \Rightarrow A_v \approx \frac{R_E + R_F}{R_E} = 1 + \frac{R_F}{R_E}$$

(c) $R_E = 50 \Omega$

$$\Rightarrow A_F = 1 + R_F/R_E = 25 \text{ V/V}$$

$$\Rightarrow R_F/R_E = 24 \text{ and } R_F = 24 R_E = 1'.$$

(d) $I_{G1} = 1 \text{ mA}$, $I_{G2} = 2 \text{ mA}$, $I_3 = 5 \text{ mA}$

$$3 = 100$$

$$r_{e1} = \frac{25\text{mV}}{1\text{mA}} = 25\Omega, r_{e2} = 12.5\Omega, r_{e3} =$$

$$A_1 = \frac{-R_{C1} \parallel r_{\pi 2}}{r_{e1} + R_E \parallel R_F} = -10$$

$$\Rightarrow R_{C1} \parallel R_{E2} = 10(25 + 50 \parallel 1.2k) = 730$$

$$\Rightarrow R_{C1} = 1.75 \text{ k}\Omega$$

$$A_2 = \frac{-R_{C2} \parallel \{ \beta (r_{e1} + R_E + R_F) \}}{r_{e2}} = -$$

$$\Rightarrow R_{L2} \parallel 125.5k = 5 \times 12.5 = 62.5.$$

$$\Rightarrow R_{C2} = 628.1 \Omega$$

$$A_3 = \frac{R_E + R_F}{r_{i3} + R_E + R_F} = \frac{1.25}{1.255} = 0.996$$

(e) $\therefore A_1 A_2 A_3 = 10 \times 50 \times 0.996 = 498 \text{ V}$

$$AP_3 = 498(50/1250) = 19.92$$

$$A_F = \frac{A}{1+A\beta} = 238 \text{ V/V}$$

$$H) R_i = (\beta + 1)(r_e + R_E || R_F)$$

$$\begin{aligned} \therefore R_i &= 101(25 + 4.8) = 7.37 \text{ K}\Omega \\ R_{if} &= R_i(1 + 19.92) = 154 \text{ K}\Omega \\ R_o &= 1.25 \text{ K}\Omega \parallel (r_{e3} + R_{c2} \parallel 101) = 11.12 \Omega \\ R_{of} &= \frac{R_o}{1 + 19.92} = 0.53 \Omega \end{aligned}$$

Section 8.5 Series-Series Feedback

8.36

For $A\beta \gg 1$: $A_F = \frac{A}{1 + A\beta} \Rightarrow \frac{1}{\beta} \equiv A_F^*$

Here, $\beta = \frac{V_f}{I_o} = \frac{R_{E2} \times R_{E1}}{R_{E2} + R_F + R_{E1}}$
 $= \frac{100 \times 100}{100 + 640 + 100} = 11.9 \Omega$

$$\frac{I_o}{V_s} \approx A_F^* \equiv \frac{1}{\beta} = 84 \mu\text{A/V} \quad (\text{cf. } 83.7)$$

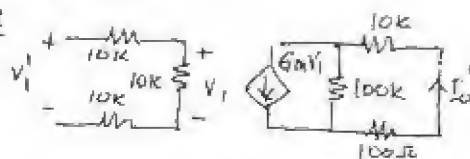
$$\frac{V_o}{V_s} = -\frac{I_o R_{E3}}{V_s} = -84 \times 0.6 = -50.4 \text{ V/V} \quad (\text{cf. } 50.2)$$

8.37

$A = G_m = 100 \text{ mA/V}$ $\beta = 0.1 \text{ V/mA}$

$r_{in} = 10 \text{ K}\Omega$, $r_{out} = 100 \text{ K}\Omega$

A. circuit



$$V_i = V_i' \frac{10}{10 + 10 + 10} = V_i' / 3$$

$$I_o' = \frac{G_m V_i \cdot 100}{100 + 10 + 0.1} = 30.28 \text{ V}' \text{ mA}$$

$$A = \frac{I_o'}{V_i} = 30.28 \text{ mA/V}$$

$$A_F = \frac{A}{1 + A\beta} = \frac{30.28}{1 + 30.28(0.1)} = 7.52 \text{ mA/V}$$

$$\begin{aligned} R_i &= R_s + R_{id} + R_i = 30 \text{ K}\Omega \\ R_{if} &= R_i(1 + A\beta) = 120.8 \text{ K}\Omega \\ R_{im} &= R_{if} - R_s = 110.8 \text{ K}\Omega \end{aligned}$$

$$\begin{aligned} R_o &= R_L + R_{of} + R_2 = 110.1 \text{ K}\Omega \\ R_{of} &= R_o(1 + A\beta) = 443.4 \text{ K}\Omega \\ R_{out} &= R_{of} - R_L = 433.4 \text{ K}\Omega \end{aligned}$$

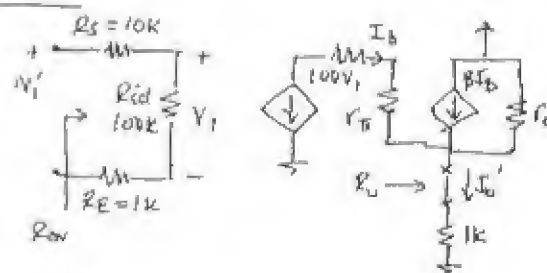
8.38

For $A\beta \gg 1$: $I_o/V_s \approx 1/\beta$

R_E samples I_o/α and $V_E = I_o R_E / \alpha$

$$\beta = \frac{V_f}{I_o} = R_E \times A_F \Rightarrow \frac{1}{\beta} = \frac{1}{R_E} \quad \text{QED}$$

A. circuit



For $\frac{I_o}{V_s} = 1 \text{ mA/V} \approx \frac{1}{\beta} \approx \frac{1}{R_E} \Rightarrow R_E = 1 \text{ K}\Omega$

$$V_i = V_i' \frac{R_{id}}{R_s + R_{id} + R_E} = \frac{100 V_i'}{100 + 10 + 1} = 0.9 V_i'$$

$$I_b = \frac{G_m V_i}{1 + r_{\pi} + (1 + \beta)(R_E \parallel r_o)}$$

$$I_o' = \frac{(\beta + 1) I_b (R_E \parallel r_o)}{R_E}$$

$$\frac{I_o'}{V_i'} = \frac{1}{R_E} \frac{(\beta + 1)(R_E \parallel r_o) 100 \times 0.9}{1 + r_{\pi} + (1 + \beta)(R_E \parallel r_o)} \rightarrow \frac{1}{R_E}$$

$$A = \frac{I_o'}{V_i'} = \frac{1}{1} \cdot \frac{101(1 \times 100) \times 90}{1 + 2.5 + 101(1 \parallel 100)} = 87 \text{ mA/V}$$

$$A_F = \frac{I_E}{V_s} = \frac{87}{1 + 87 \times 1} = 0.989 \text{ mA/V}$$

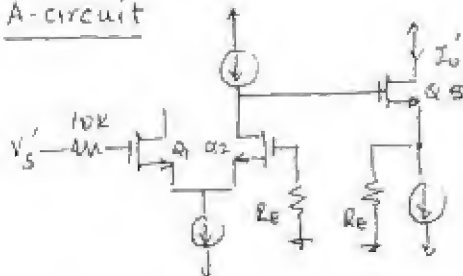
Thus $\frac{I_o}{V_s} = \frac{\beta}{\beta + 1} \cdot \frac{I_E}{V_s} = 0.989 \times 0.99 = 0.98 \text{ mA/V}$

$$\begin{aligned}
 R_i &= 10 + 100 + 1 = 111 \text{ k}\Omega \\
 R_{if} &= 111 \times 88 = 9768 \text{ k}\Omega \\
 R_{IN} &= R_{if} - R_s = 9758 \text{ k}\Omega \approx 9.8 \text{ M}\Omega \\
 R_o \text{ (looking into } x \text{ in A circuit)} \\
 &= R_E \parallel r_o + \frac{1 \text{ k} + r_s}{\beta + 1} \\
 &= (1 \parallel 100) + \frac{1 + 2.5}{101} = 1.025 \text{ k}\Omega \\
 R_{if} \text{ (in amplifier circuit)} &= 1.025 \times 88 \\
 &= 90.2 \text{ k}\Omega \\
 R_{out} &= r_o [1 + g_m (90.2 \parallel r_s)] = 9.83 \text{ k}\Omega
 \end{aligned}$$

8.39

$$\begin{aligned}
 I_1 &= 0.2 \text{ mA} / 2 = 100 \mu\text{A} \\
 I_S &= 0.8 \text{ mA} = 800 \mu\text{A} \\
 g_{m1} &= 2 \sqrt{\frac{1}{2} \cdot 20 (36/10) 100} = 120 \mu\text{A/V} \\
 g_{m5} &= 2 \sqrt{\frac{1}{2} \cdot 20 (200/10) 800} = 800 \mu\text{A/V} \\
 r_{o1} &= V_A / I_1 = 100 \text{ V} / 100 \mu\text{A} = 1 \text{ M}\Omega \\
 r_{o5} &= V_A / I_S = 100 \text{ V} / 800 \mu\text{A} = 125 \text{ k}\Omega \\
 r_{e1} &= V_T / I_1 = 25 \text{ mV} / 100 \mu\text{A} = 250 \Omega \\
 r_{e5} &= V_T / I_S = 25 \text{ mV} / 800 \mu\text{A} = 31.25 \Omega
 \end{aligned}$$

A-circuit



$$\beta = \frac{V_F}{I_O} = \frac{I_O R_E}{I_O} = R_E \frac{V_A}{I_O}$$

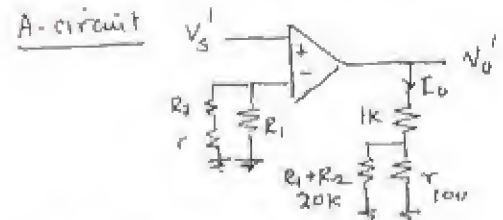
$$\begin{aligned}
 A &\equiv \frac{I_O'}{V_S'} \approx \frac{g_{m1} r_{o2}}{2} \cdot \frac{1}{R_E \parallel r_{o5}} \\
 &= \frac{120 \times 1000}{2} \times \frac{1}{9.25} = 6.48 \text{ mA/V} \\
 \Rightarrow \frac{I_O}{V_S} &= \frac{6.48 \times 10^{-3}}{1 + 6.48 (10)} = 98.5 \mu\text{A/V}
 \end{aligned}$$

$$\begin{aligned}
 \frac{V_O}{V_{OS}} &= \frac{I_O (R_E \parallel R_{o5})}{V_{OS}} = \frac{98.5 \mu\text{A}}{V} \cdot \frac{9.25 \text{ V}}{100} \\
 &= 0.911 \text{ V/V} \approx 1 \text{ V/V}
 \end{aligned}$$

8.40

$$A_f \equiv \frac{I_O}{V_S} \quad (\text{Assume } (R_1 + R_2) \gg r)$$

$$\beta \equiv \frac{V_F}{I_O} = R_1 \frac{r}{r + R_1 + R_2} \frac{V_A}{I_O}$$



$$\frac{I_O'}{V_S'} = \frac{A}{r + R_L}$$

$$A_F = \frac{I_O}{V_S} = \frac{A}{1 + A\beta} = \frac{A/(r + R_L)}{1 + \frac{A}{r + R_L} \cdot \frac{r R_1}{r + R_1 + R_2}}$$

$$= \frac{A}{(R_L + r) + \frac{A r R_1}{r + R_1 + R_2}}$$

$$\Rightarrow \frac{r + R_1 + R_2}{r R_1} \approx \frac{1}{\beta}$$

(a) when $\mu = 10^5 \text{ V/V}$ and $R_1 = 100 \Omega$

$$\begin{aligned}
 A_F &= \frac{\mu = 10^5}{(1 \text{ k} + 100) + \frac{10^5 \cdot 100 \cdot 100}{100 + 100 + 1 \text{ k}}} \\
 &= \frac{10^5}{1100 + \frac{10^5 \cdot 10^4}{1200}} = \frac{0.12 \text{ mA}}{\text{V}}
 \end{aligned}$$

$$\frac{1}{\beta} = \frac{100 + 100 + 1000}{100 \times 100} = \frac{1200}{10^4} = 0.12 \text{ mA/V}$$

$$R_i' = R_{id} + R_1 = 10 \text{ k} + 100 = 10.1 \text{ k}\Omega$$

$$R_{of} = R_i' (1 + A\beta) = R_i' (1 + \frac{1}{\beta} \cdot \beta) = 20.2 \text{ k}\Omega$$

$$R_o = r_o \parallel (R_L + (r \parallel R_2)) = 100 \parallel (1050) = 91.3 \Omega$$

$$R_{of} = R_o' (1 + A\beta) = 2 \times 91.3 = 182.6 \Omega$$

(b) $\beta = V_F / I_O = I_{OC} / I_O = 100 \text{ A/V} = 100 \Omega$

$$A_F = 10^4 / [(1100) + 10^4 \cdot 100] \approx 1/100$$

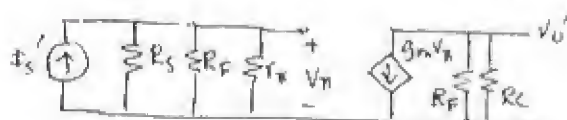
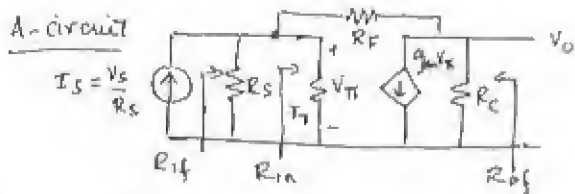
$$A_F \beta = 1 \text{ and } (1 + A\beta) = 2$$

$$R_i = R_i' (1 + A\beta) \rightarrow \infty$$

$$R_{of} = 2 (100 \parallel 1025) = 182.2 \Omega$$

Section 8.6 The Shunt-shunt and Shunt Series Feedback Amplifiers

8.41

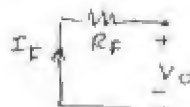


$$V_{\pi} = I_s (R_s \parallel R_F \parallel R_{in})$$

$$A \equiv \frac{V_o'}{I_s} = -g_m (R_s \parallel R_F \parallel R_{in}) (R_F \parallel R_o)$$

B-circuit

$$\beta \equiv \frac{I_F}{V_o} = -\frac{1}{R_F}$$



$$A_F \equiv \frac{V_o}{I_s} = \frac{A}{1+A\beta} = \frac{-g_m R^x}{1+g_m R^x / R_F}$$

$$\rightarrow -\frac{g_m R^x}{g_m R^x} R_F = -R_F$$

$$A_V = \frac{V_o}{I_o R_s} \approx -\frac{R_F}{R_s} \quad \text{QED}$$

For $R_s = 10\text{K}$, $R_F = 47\text{K}$, $R_o = 4.7\text{K}$

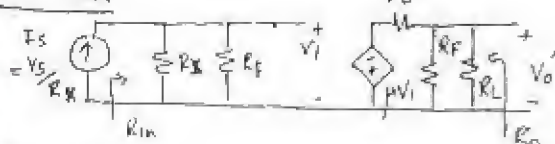
$$A_V \approx -\frac{47\text{K}}{10} = -4.7\text{V/V}$$

For $A_V = -7.5\text{V/V}$

$$R_F = A_V R_s = 7.5 \times 10 = 75\text{K}$$

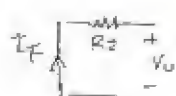
8.42

A-circuit



B-circuit

$$\beta \equiv \frac{I_F}{V_o} = -\frac{1}{R_F}$$



Here let $R_x = R_s + R_1$ and $\mu = g_m r_o$

$$A \equiv \frac{V_o'}{I_s} = -[R_x \parallel R_2][R_2 \parallel r_o] g_m$$

$$A_F = \frac{V_o}{I_s} = \frac{A}{1+A\beta} = \frac{-g_m [R_x \parallel R_2][R_2 \parallel r_o]}{1+(A)(-1/R_2)}$$

$$= -g_m \frac{R_x R_2}{R_x + R_2} \cdot \frac{R_2 r_o}{R_2 + r_o}$$

$$1 + g_m \frac{R_x R_2}{R_x + R_2} \cdot \frac{R_2 r_o}{R_2 + r_o} \left[\frac{-1}{R_2} \right]$$

$$\xrightarrow{\text{Algebra}} -\frac{R_2}{\beta} = -\frac{1}{\beta}$$

$$\text{Thus } \frac{V_o}{I_s R_x} = \frac{V_o}{I_s} = \frac{1}{\beta R_x} = -\frac{R_2}{R_1 + R_2}$$

$$R_{in} = (R_s + R_1) \parallel R_2 = (10\text{K} + 1\text{M}) \parallel 4.7\text{M}$$

$$= 1.01\text{M} \parallel 4.7\text{M} = 0.83\text{M}\Omega$$

$$\text{Now } g_m = \frac{2I_D}{V_{ov}} = \frac{2 \times 1}{0.8 - 0.6} = \frac{2}{0.2} = 10\text{mA/V}$$

$$r_o = \frac{V_A}{I} = \frac{30\text{V}}{1\text{mA}} = 30\text{K}\Omega$$

$$\text{Hence } A = -\frac{[(R_s + R_1) \parallel R_2][R_2 \parallel r_o] g_m}{1 + \frac{[(R_s + R_1) \parallel R_2][R_2 \parallel r_o] g_m}{R_2}}$$

$$= -10 [1.01\text{M} \parallel 4.7\text{M}] [4.7\text{M} \parallel 0.03\text{M}]$$

$$= -10 [83\text{K}] [29\text{K}] \text{V/mA}$$

$$= -24100$$

$$1 + A\beta = 1 + (24100 \times \frac{1}{4700}) = 6.13$$

$$A_F = \frac{-24100}{6.13} = -3931\text{K}\Omega$$

$$\text{Hence } \frac{V_o}{V_i} = \frac{V_o}{I_s (R_s + R_1)} = \frac{-3931\text{K}}{1010} \approx -3.89\text{V/V}$$

$$R_o' = R_2 \parallel r_o = 4.7\text{M} \parallel 30\text{K} = 29.8\text{K}\Omega$$

$$R_{of} = R_o' / (1 + A\beta) = 29.8 / 6.13 = 4.86\text{K}\Omega$$

$$R_i' = (R_s + R_1) \parallel R_2 = 1010 \parallel 4.7 = 0.83\text{M}\Omega$$

$$R_{if} = R_i' / (1 + A\beta) = 0.83 / 6.13 = 136\text{K}\Omega$$

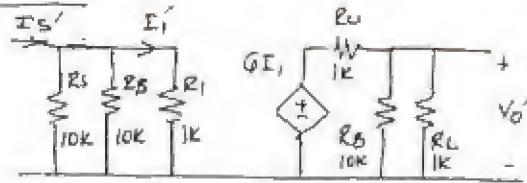
$$R_{in} = R_{if} - R_1 = 136\text{K} - 10\text{K} = 126\text{K}$$

8.43

$G_m = 100\text{mA/V}$, $R_{inpt} = 1\text{K}$, $R_{outpt} = 1\text{K}$

$R_1 = 10\text{K}$, $R_2 = 100$, $R_s = 10\text{K}$, $R_L = 1\text{K}$

A-circuit



$$\beta = 0.1$$

$$A \equiv \frac{V_o'}{I_s'} = \frac{(R_S \parallel R_B) G_1}{(R_S \parallel R_B) + R_1} \cdot \frac{(R_B \parallel R_L)}{(R_B \parallel R_L) + R_o}$$

$$= \frac{(10 \parallel 10) 100}{(10 \parallel 10) + 1} \cdot \frac{(10 \parallel 1)}{(10 \parallel 1) + 1} = 75.75 \text{ V/mA}$$

$$A_F \equiv \frac{A}{1 + AB} = \frac{75.75}{1 + 75.75 \times 0.1} = 8.83 \text{ V/mA}$$

$$(1 + AB) = 8.575$$

$$R_i = R_S \parallel R_B \parallel R_1 = 833 \Omega$$

$$R_{if} = R_i / (1 + AB) = 97.1 \Omega$$

$$R_{in} \parallel R_S = R_{if} \rightarrow R_{in} \approx 89.7 \Omega$$

$$R_o' = (R_D \parallel R_B \parallel R_L) = 476 \Omega$$

$$R_{of} = R_o' / (1 + AB) = 55.5 \Omega$$

$$R_{out} \parallel R_L = R_{of} \rightarrow R_{out} \approx 58.76 \Omega$$

$$AB = 56 \Rightarrow 1 + AB = 57$$

$$A_F = \frac{-555.5}{1 + 555.5 \times 0.1} = -9.8 \text{ mA}$$

$$R_i' = R_F + R_S = 100 \text{ k}\Omega$$

$$R_{if} = R_i' / (1 + AB) = 1.58 \text{ k}\Omega$$

$$R_{of} = (R_F \parallel R_S) + r_{o2}$$

$$= 9 \text{ k}\Omega + 20 \text{ k}\Omega = 29 \text{ k}\Omega$$

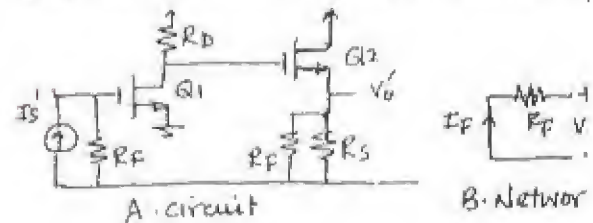
$$R_o \approx r_{o1} (1 + g_m R_{of}) =$$

$$= 20 \text{ k}\Omega (1 + 5 \times 29)$$

$$\approx 2.92 \text{ M}\Omega$$

8.45

Here shunt-shunt: sample V_o return I_i



$$A \equiv \frac{V_o'}{I_s'} = -g_{m1} R_D R_F \text{ (neglecting } r_i)$$

$$\beta \equiv \frac{I_F}{V_o} = -1/R_F, \quad AB = g_{m1} R_D$$

$$A_F \equiv \frac{V_o}{I_s} = \frac{A}{1 + AB} = \frac{-g_{m1} R_D R_F}{1 + g_{m1} R_D R_F / R}$$

$$= \frac{-5 \times 10 \times 90}{1 + 5 \times 10}$$

$$= -4500 / 51 = -88.2$$

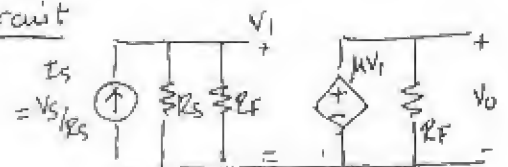
$$R_i' = R_F = 90 \text{ k}\Omega \rightarrow R_{if} = R_i' / (1 + AB) = 1.76$$

$$R_o' = r_{o1} \parallel R_F \parallel R_S = 20 \parallel 90 \parallel 20 = 6.2 \text{ k}\Omega$$

$$\Rightarrow R_{of} = R_o' / (1 + AB) = 121.6 \Omega$$

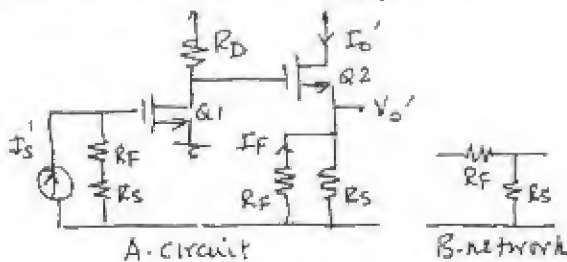
8.46

A-circuit



8.44

Here shunt-series: sample I_o , return I_F
Because Q_2 is voltage-driven device, unlike BJT
we find $I_o = V_o / R$ as voltage follower.



$$A \equiv \frac{I_o'}{I_s'} = \frac{-g_{m1} R_D (R_S + R_F)}{(R_S \parallel R_F)} = -555.5$$

$$\beta \equiv \frac{I_F}{I_o} = \frac{R_S}{R_F + R_S} = \frac{10}{100} = 0.1$$

$$A_F \equiv \frac{I_o}{I_s} = \frac{-g_{m1} R_D (R_F + R_S)}{(R_S \parallel R_F) + (R_F + R_S)}$$

$$\rightarrow \frac{R_F + R_S}{R_S} = 1 + R_F / R_S$$

$$\beta = -1/R_F$$

$$V_o = -\mu V_i R_F$$

$$V_i = I_s (R_S \parallel R_F)$$

$$\therefore V_o = -\mu I_s (R_S \parallel R_F) R_F$$

$$A \equiv \frac{V_o}{I_s} = -\mu \frac{R_S R_F}{(R_S + R_F)} \cdot R_F$$

$$A_F = \frac{A}{1 + A\beta} = -\mu \frac{(R_S \parallel R_F) R_F}{1 + \mu (R_S \parallel R_F) R_F / R_F}$$

$$= -\frac{\mu (R_S \parallel R_F) R_F}{1 + \mu (R_S \parallel R_F)}$$

$$\frac{V_o}{V_s} = \frac{V_o}{I_s R_S} = -\frac{\mu (R_S \parallel R_F) R_F}{[(R_S + R_F) + \mu (R_S R_F)] R_S}$$

$$\Rightarrow -\frac{\mu (R_S R_F)}{\mu (R_S R_F)} \cdot \frac{R_F}{R_S} = -\frac{R_F}{R_S}$$

QED

(b) For circuit of Fig P8.46 (b)

$$I_B = \frac{V_{CC} - V_{BE}}{\frac{R_1}{\beta + 1} + R_2} = \frac{10 - 0.7}{\frac{10}{101} + 15} = \frac{9.3}{15.099} \approx 0.616 \text{ mA}$$

$$I_C = 100 I_B = 1.1 \text{ mA}$$

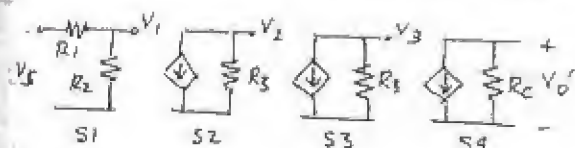
$$r_e = V_T / I_C = 22.6 \Omega$$

$$r_{\pi} = (\beta + 1) r_e = 2.286 \text{ k}\Omega$$

$$g_m = \beta / r_{\pi} = 100 / 2.286 \text{ k}\Omega \rightarrow 43.7 \text{ mA/V}$$

$$R_{in} = (15 \parallel 10 \parallel 2.286) \text{ k}\Omega \approx 1.5 \text{ k}\Omega$$

$$R_C \parallel R_L / r_{\pi} = (7.5 \parallel 6 \parallel 2.286) \approx 1.35 \text{ k}\Omega$$



For S1: $R_1 = R_S, R_2 = R_{in}$

$$\therefore V_1 = 1.5 / 11.5 \times V_s = 0.13 V_s$$

For S2: $R_3 = R_C \parallel R_L \parallel r_{\pi}$

$$\therefore \frac{V_2}{V_1} = -g_m R_3 = -43.7 \times 1.35$$

$$\approx -59 \text{ V/V}$$

For S3: Same as S2 $\therefore \frac{V_3}{V_2} = -59 \text{ V/V}$

For S4: $\frac{V_o}{V_3} = -g_m R_C = -43.7 \times 7.5$

$$\approx -327.75 \text{ V/V}$$

$$\frac{V_o}{V_s} = -0.13 \times 59 \times 59 \times 327.75$$

$$\Rightarrow \frac{V_o}{V_s} = -1.488 \times 10^5$$

Because we have ignored r_o etc let us estimate $V_o/V_s = -1 \times 10^5$ which is quite large.

Then $A_F = \frac{A}{1 + A\beta} \approx 100$ needed

$$= \frac{10^5}{1 + 10^5 \beta} \approx \frac{1}{\beta} = 100$$

Select R_F so that $R_F/R_S = 100$

$$\Rightarrow R_F = 100 \times 10 \text{ k}\Omega = 1 \text{ M}\Omega$$

We can ignore loading effect of R_F in A-circuit. R_L will cause loading of R_C $\therefore V_L = (R_L / (R_C + R_L)) V_o$

$$= (1/8.5) = 0.11 V_o$$

Now $A_o \approx 10^4$

$$A_F' = \frac{10^4}{1 + 10^4/100} \approx 99.00$$

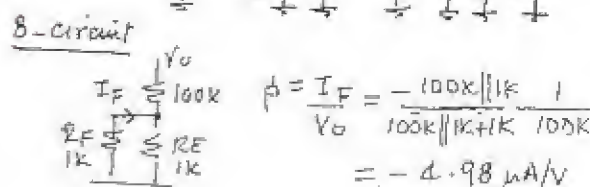
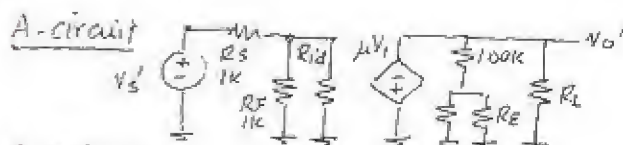
8.47

(a) To lower R_{in} and raise R_{out}
SHUNT - SERIES

(b) To raise R_{in} and R_{out}
SERIES - SERIES

(c) To lower R_{in} and R_{out}
SHUNT - SHUNT

8.48



$$V_i = (1 \parallel 100 \parallel 1.99) \times 10^3 I_S' = 661.2 I_S'$$

$$\frac{V_o'}{I_S'} = - \frac{661.2 (10)^4 \cdot 2k \parallel 100.5k}{2k \parallel 100.5k + 1k}$$

$$= -4.38 \times 10^6 = -4.38 \text{ M}\Omega$$

$$\Rightarrow \frac{V_o}{V_S} = \frac{A}{1+AB} = \frac{-4.38 \times 10^6}{1 + 4.38 \times 4.98}$$

$$= -191.86 \times 10^3 \text{ V/V}$$

$$\frac{V_o}{V_S} = \frac{V_o}{I_S R_S} = -191.9 \text{ V/V}$$

$$R_i = (1 \parallel 100 \parallel 1.99)k = 661.2k$$

$$R_{if} = R_i / 22.8 = 29 = R_{in} \parallel R_S$$

$$\Rightarrow R_{in} = 29.4\Omega$$

$$R_o = 1k \parallel 100.5k \parallel 2k = 662.2\Omega$$

$$R_{of} = R_{out} \parallel R_L = R_o / 22.8 = 29\Omega$$

$$\Rightarrow R_{out} = 29.5\Omega$$

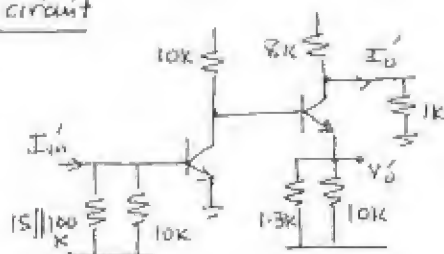
8.49

$$\beta = -1/R_F = -10^{-4}$$

$$I_{E1} = I_{E2} = 1 \text{ mA} \Rightarrow r_{e1} = r_{e2} = 25\Omega$$

$$r_{\pi 1} = r_{\pi 2} = 2.5k\Omega, r_o = 100k$$

A-circuit



$$\mu = \frac{V_{E2}}{V_{B1}} = \frac{-10k \parallel r_o \parallel \beta(1.3k \parallel 100k)}{25}$$

$$\times \frac{1.3k \parallel 10k}{25 + 1.3k \parallel 10k}$$

$$= -337(0.979) = -330 \text{ V/V}$$

$$\frac{V_o'}{I_{in}'} = (15k \parallel 100k \parallel 10k \parallel 2.5k)(-330)$$

$$= -572 \text{ k}\Omega$$

$$\Rightarrow \frac{V_o}{I_{in}} = \frac{-572}{1 + 572(0.1)} = -9.83 \text{ k}\Omega$$

$$R_{if} = 15k \parallel 100k \parallel 10k \parallel 2.5k = 1.73k$$

$$R_{in} = R_{if} = 1.73k / 58.2 = 29.7\Omega$$

$$I_{out} = \frac{8k}{1k + 8k} \cdot \frac{V_o}{1.3k \parallel 10k} = 0.773 \times 10^{-3} \text{ V}$$

$$\Rightarrow \frac{I_o}{I_{in}} = -9.83 \times 0.773 = -7.6 \text{ A/A}$$

$$\text{cf. Ex 8.4 } \frac{I_o}{I_{in}} = -7.57 \text{ A/A}, R_{in} = 30\Omega$$

8.50

$$I_o/I_S = 100 \text{ A/A}, R_{in} = 1k, R_{out} = 10k$$

$$\beta = 0.1 \text{ Shunt-series topology}$$

$$A_D = \frac{I_o'}{I_S'} = 100$$

$$A_F = \frac{A_D}{1 + A_D \beta} = \frac{100}{1 + 100(0.1)} = 9.09 \text{ A/A}$$

$$R_i = 1k\Omega$$

$$\Rightarrow R_{if} = R_i / (1 + AB) = 90.9\Omega$$

$$R_o = 10k\Omega$$

$$\Rightarrow R_{of} = R_o (1 + AB) = 110k\Omega$$

8.51

$$\text{Neglect } I_{B1}; I_{B1} \approx \frac{200}{100} = 2\mu\text{A}$$

$$V_{BE} = 0.7 \text{ V} \therefore V_{B1} = +0.7 \text{ V}$$

$$\text{But no d.c. component in } V_S$$

$$\therefore I_{E1} (\text{into } V_S) = 0.7 / 10k = 0.07\mu\text{A}$$

$$\text{Thus } I_F = I_{E1} + I_{B1} = 0.07 + 0.002$$

$$= 0.072 \text{ mA}$$

$$V_{E2} = 0.7 + 10 \times 0.072 = 0.7 + 0.72 = 1.42$$

$$I_{C2} = 1.42 / 140 + 0.072 = 10.2 \text{ mA}$$

$$I_{B2} = I_{E2} / (\beta + 1) = 0.1 \mu\text{A} \approx \frac{1}{2} 200\mu\text{A}$$

1k rate:

$$I_{B1} = \frac{200\mu\text{A} - 100\mu\text{A}}{100} = 0.001\mu\text{A}$$

$$V_{E2} = 0.7 + 10 \times 0.073 = 1.41 \text{ V}$$

$$I_{B2} = 1.41 / 0.140 + 0.071 = 10.1 \text{ mA}$$

$$I_{B2} = 10.1 / 101 = 100\mu\text{A} \therefore I_{C2} = 10 \text{ mA}$$

$$V_{B2} = V_{E2} + V_{BE} = 1.41 + 0.7 = 2.11 \text{ V}$$

$$V_o = 10 - 10 \times 500\Omega = +5 \text{ V}$$

$$r_{e1} = \frac{V_T}{I_E} = \frac{25\text{mV}}{0.1\text{mA}} = 250\Omega, r_{e2} = 25\Omega$$

$$\beta = \frac{R_E}{R_F + R_E} = \frac{140}{10\text{k} + 140} \approx 0.0138$$

A-circuit



$$V_{B1} = 10.14\text{k} \parallel 10\text{k} \parallel \beta(250)I_S'$$

$$= 4.2 \times 10^3 I_S'$$

$$\Rightarrow \frac{I_{O1}}{I_S'} = \frac{4.2 \times 10^3 (\beta + 1)(r_{e2} + 10\text{k} \parallel 140)}{250}$$

$$\times \frac{1}{(r_{e2} + 10\text{k} \parallel 140)}$$

$$= 1.69 \times 10^3 \text{ A/A}$$

$$A_F \equiv \frac{I_O}{I_S} = \frac{A}{1 + A\beta} = \frac{1.69 \times 10^3}{1 + 1.69 \times 10^3 \times (0.0138)}$$

$$= 69.6$$

$$\Rightarrow \frac{V_O}{V_S} = \frac{I_O R_L}{I_S R_S} = \frac{500 \cdot 69.6}{10^4} = 3.5 \text{ V/V}$$

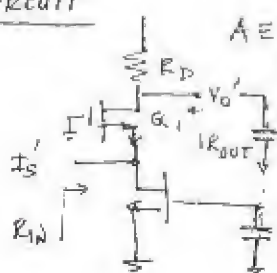
$$R_i = 10\text{k} \parallel 10.14\text{k} \parallel 25\text{k} = 4.2\text{k}\Omega$$

$$R_{if} = R_i / (1 + A\beta) = \frac{4.2}{1 + 23.3} = 172.8\Omega$$

$$\Rightarrow R_{in} \parallel R_S \Rightarrow R_{in} = 175.8\Omega$$

8.52

A-circuit

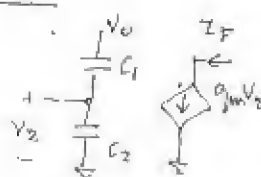


$$A \equiv \frac{V_O'}{I_S'} = [R_D \parallel X_C] = R_D$$

Neglecting loading of C's

$$A_F = \frac{A}{1 + A\beta}$$

B-circuit



$$\beta = \frac{C_1}{C_1 + C_2} g_{mf}$$

$$= \frac{1}{10} \times 1 \frac{\text{mA}}{\text{V}}$$

Here $g_{m1} = 5\text{mA/V}$ $g_{mf} = 1\text{mA/V}$
 $R_D = 10\text{k}\Omega$

Thus $A = 10\text{k}\Omega$

$$A_F = \frac{10\text{k}}{1 + 10\text{k}(0.1)} = 5\text{k}\Omega$$

$$R_{in} = (R_D \parallel r_o) \rightarrow R_D$$

$$R_{if} = R_D / (1 + A\beta) \text{ shunt} = \frac{R_D}{2} = 5\text{k}\Omega$$

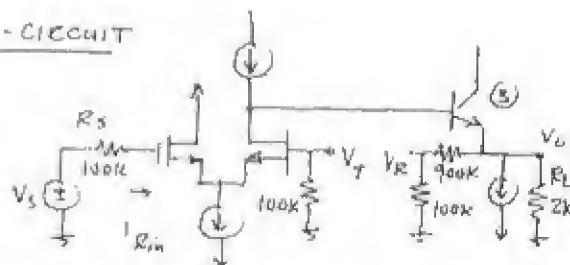
$$R_{out} = R_D / (1 + A\beta) = \frac{R_D}{2} = 5\text{k}\Omega$$

Section 8.7

Determining the Loop Gain

8.53

A-circuit



$$V_R = -\frac{[100\text{k} \parallel (\beta + 1)(r_{e2} + (1\text{M} \parallel \frac{20\text{k}}{2} \parallel R_L))]}{2/g_{m1}}$$

$$\times \frac{r_{e2}}{[r_{e2} + (1\text{M} \parallel \frac{20\text{k}}{2} \parallel R_L)]}$$

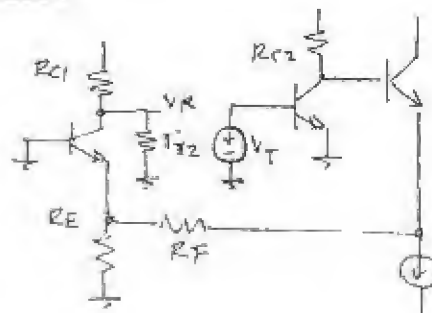
$$= -\frac{[100\text{k} \parallel 168\text{k}]}{2} \times \frac{5}{1665} = -31.25$$

$$R_O = [1\text{M} \parallel \frac{20\text{k}}{2} \parallel R_L] \parallel [\frac{20\text{k}}{2} / \beta + r_{e3}]$$

$$= 623\Omega$$

which agree with previous solution

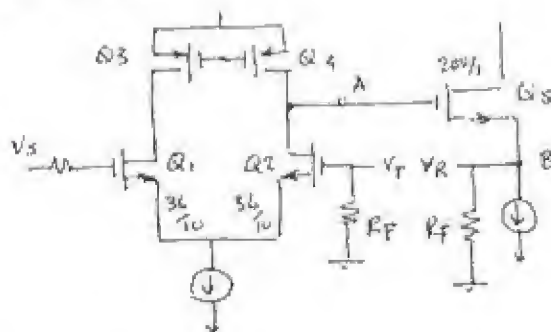
8.54



$$\frac{V_R}{V_T} = \frac{g_m z R_C (\beta + 1)}{R_C + (\beta + 1) [r_{e3} + R_F + (R_{E1} || r_{e1})]} \times \frac{\alpha R_E (R_{E1} || r_{e2})}{R_E + r_{e1}} \quad \alpha \approx 1$$

Q. ED

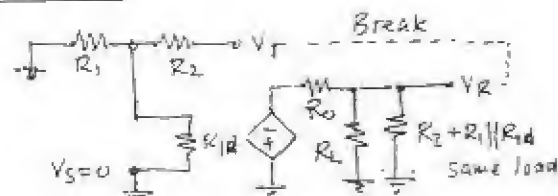
8.55



$$\begin{aligned}
 V_T &= V_{O2} \quad \text{and} \quad V_S \rightarrow 0 \\
 V_A &= -g_{m2}(r_{O2} \parallel r_{O4}) \\
 V_B &= V_A \frac{(R_F \parallel r_{O5})}{(R_F \parallel r_{O5}) + 1/g_{m5}} \\
 A\beta &= \frac{-V_T}{V_R} = +g_{m2} \frac{(r_{O2} \parallel r_{O4})(R_F \parallel r_{O5})}{(R_F \parallel r_{O5}) + 1/g_{m5}} \quad \text{SED}
 \end{aligned}$$

 $s \in D$

8.56



$$\frac{V_R}{V_T} = \frac{-\mu R_L \left((R_2 + R_1 \parallel R_{id}) \right)}{R_D + R_L \parallel (R_2 + R_1 \parallel R_{id})} \cdot \frac{R_1 \parallel R_{id}}{R_2 + R_1 \parallel R_{id}}$$

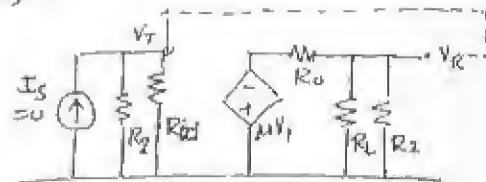
For $(R_1 + R_2) \twoheadrightarrow R_L$ and $R_{id} \twoheadrightarrow R_1$
and $R_0 \ll R_L$

$$\frac{V_R}{V_T} \approx -\mu \cdot I \cdot \frac{R_1}{R_1 + R_2} = -\frac{\mu R_1}{R_1 + R_2}$$

$$= -A_B$$

$$= -AB$$

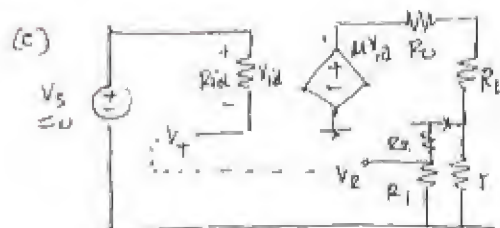
(b) $I_5 = 0$



$$\frac{V_R}{V_T} = -\mu \frac{R_L \parallel R_2}{R_o + R_L \parallel R_2}$$

For $R_u \ll R_L$

$$\frac{V_R}{V_+} \approx -\mu = -A\beta.$$



$$\frac{V_R}{V_T} = \frac{-\mu \cdot [Y // (R_1 + R_2)]}{R_0 + R_L + [Y // (R_1 + R_2)]} \cdot \frac{R_1}{R_1 + R_2}$$

For $1 \ll (R_1 + R_2)$ and $R_0 \ll R_L$

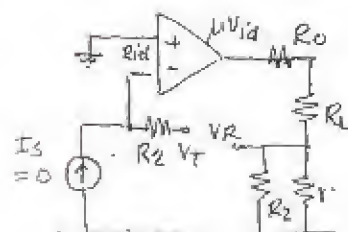
$$\frac{V_E}{V_T} \approx \frac{-M R}{R_1 + r} \cdot \frac{R_1}{R_1 + R_2} = -A\beta$$

Note: breaking at $R_2 - r$ is simpler

$$\frac{V_R}{V_T} = \frac{-\mu R_1}{R_{th}R_1 + R_2} \cdot \frac{r}{R_0 + R_2 + r}$$

$$\frac{V_R}{V_T} = \frac{-\mu R_1}{R_{in} R_1 + R_2} \cdot \frac{r}{R_0 + R_L + r}$$

(2)

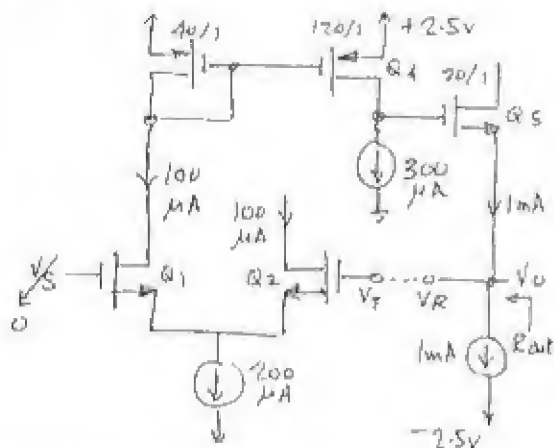


$$V_{id} = V_T \frac{R_{id}}{R_2 + R_{id}}$$

$$\frac{V_R}{V_T} = - \frac{R_{id}}{R_{id} + R_2} \mu \frac{(r || R_2)}{(r || R_2) + R_L + R_O}$$

$$A_{\beta} = \mu \frac{r}{r + R_L} \quad \text{for } R_{id} \gg R_1, R_2 \quad R_O \ll R_L$$

0.57



From PB.33 $g_{m1} = g_{m2} = 693 \mu A/V$

$$q_{m3} = 693 \mu A/V, q_{m4} = 2078 \mu A/V$$

$$g_{m5} = 1550 \mu A/V \quad r_{o5} = 24 k\Omega$$

$$Y_{01} = Y_{02} = Y_{03} = 240\text{K}\Omega, Y_{04} = 80\text{K}\Omega$$

$$R_{out} = (r_{o5} || r_{o5}) = 12 \text{ k}\Omega$$

$$i_{C1} = -\alpha_{FEM} I_{VT}$$

$$i_{c4} = -3 g_{m1} V_T$$

$$V_{C4} = -3 a_{gm1} V_T (r_{o4} \parallel r_{o4})$$

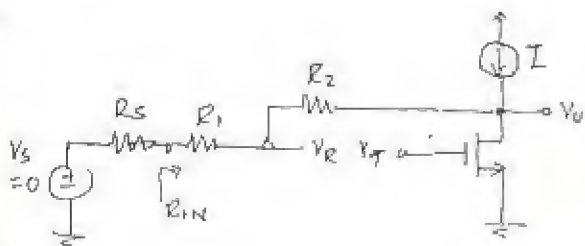
$$V_{S5} = V_{C4} = V_{D2}$$

$$\therefore \frac{V_R}{V_T} = -3 \ln \left(\frac{r_{01}}{3} \right) = -\frac{3}{2} \ln r_{01}$$

$$A_{\beta} = -\frac{V_R}{V_i} = \frac{3 \text{ mA} \cdot 10 \text{ k}\Omega}{2} = 83.16$$

$$R_0 = (r_{05} || r_{\omega 5}) = 12 \text{ k}\Omega$$

8.58



Apply V_T in the $N_S = 0$

$$\frac{V_0}{V_1} = -g_m [R_2 + R_1 + R_S] \parallel Y_0$$

$$\frac{N_R}{Y_+} = -g_m \frac{[R_2 + R_1 + R_S] \parallel R_O}{[R_2 + R_1 + R_S]} \cdot \frac{[R_1 + R_S]}{[R_2 + R_1 + R_S]}$$

$$= \frac{-g_m(R_1 + R_5) v_o}{R_1 + R_2 + R_5 + v_o}$$

$$= -A\beta$$

For $I = 1 \text{ mA}$, $V_{GS} = 0.8 \text{ V}$, $V_F = 0.6 \text{ V}$

$$V_A = 30V, R_S = 10k, R_1 = 1M, R_2 = 4.7M$$

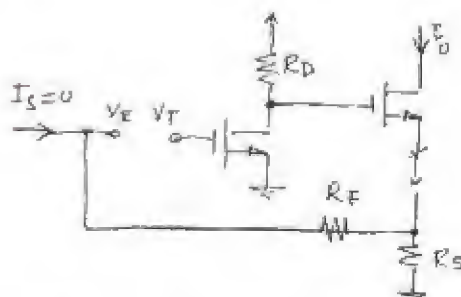
$$f_m = \frac{2I}{V_{OV}} = \frac{2}{0.8 - 0.6} = \frac{2}{0.2} = 10 \text{ mA/V}$$

$$r_o = V_A / I = 30\text{V} / 1\text{mA} = 30\text{k}\Omega$$

$$\text{Then } A\beta = \frac{10 \times 10^{-3} (10K + 10^3K) 30K}{1M + 4.7M + 10K + 30K}$$
$$= \frac{10 \times 1000 \times 30 \times 10^{-3}}{5740}$$

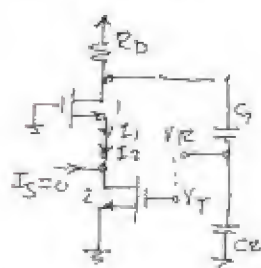
$$= 52.5 \times 10^{-3}$$

8.59



$$\frac{V_E}{V_T} = (g_{m2} R_S)(-g_{m1} R_D) = -g_{m1} g_{m2} R_D R_S = -A_{\beta}$$

8.60



$$\frac{V_R}{V_T} = \frac{\frac{1}{5C_2}}{\frac{1}{5C_1} + \frac{1}{5C_2}} \cdot \beta_{m2} R_D$$

$$-AB = \frac{C_1}{C_1 + C_2} \cdot y_{m2} K_D$$

Since $I_1 = I_2$

Section 8.8 The Stability Problem

8.61

$$A(s) = \frac{10^5}{1 + s/100}$$

$$\text{Ang}(A) = -\tan^{-1} \frac{\omega}{100} - 2 \tan^{-1} \frac{\omega}{10^4}$$

at ω_{180} : $\text{Ang}(A) = -180^\circ$ for $\omega_{180} \gg 100$

$$\Rightarrow 180^\circ = 90^\circ + 2 \tan^{-1} \left[\frac{\omega_{180}}{10^4} \right]$$

$$\text{hence } \tan^{-1} \frac{\omega_{180}}{10^4} = \frac{90^\circ}{2}$$

$$\text{i.e. } \frac{\omega_{180}}{10^4} = \tan(45^\circ) = 1$$

$$\therefore \omega_{180} = 10^4 \text{ rad/s}$$

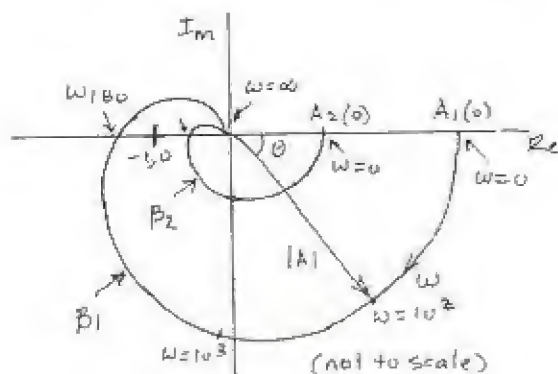
$$|AB| = \frac{10^5 \beta}{\sqrt{1 + (10^4/10^2)^2}} \cdot \frac{1}{(\sqrt{1+1})^2} = 1$$

$$\Rightarrow \beta = 0.002$$

$$A_f(0) = \frac{10^5}{1 + 10^5(0.002)} \approx 500 \text{ V/V}$$

8.62

ω	$\text{Ang}(A)$	$ A/B $	$ A/B $
0	0	10^5	10^2
10^2	45	7.07×10^4	70.7
10^3	95.7	9.85×10^3	9.85
10^4	180	500	0.5
∞	0	0	0



8.63

$$A(s) = \frac{10^3}{1 + s/10^4}$$

$$\beta(s) = \frac{K}{(1 + s/10^4)^2}$$

$$\text{Ang}(AB) = -\tan^{-1} \frac{\omega}{10^4} - 2 \tan^{-1} \frac{\omega}{10^4}$$

$$= -3 \tan^{-1} \frac{\omega}{10^4}$$

$$\text{For } 180^\circ \quad \omega_{180} = \sqrt{3} \times 10^4 \text{ rad/s}$$

$$\text{For } |AB(\omega_{180})| < 1$$

$$\frac{10^3}{\sqrt{1 + (\sqrt{3})^2}} \cdot \frac{K}{1 + (\sqrt{3})^2} < 1$$

$$\Rightarrow K < 0.008$$

8.64

$$A(s) = \frac{1000}{(1 + s/10^4)(1 + s/10^5)^2}$$

and β is independent of frequency

$$\text{Ang}(A) = -\tan^{-1} \frac{\omega}{10^4} - 2 \tan^{-1} \frac{\omega}{10^5}$$

$$\text{try } \omega = 10^4: \theta = 45^\circ + 2 \times 5.7 = 56.4^\circ$$

$$\text{try } \omega = 10^5: \theta = 84.2^\circ + 2 \times 45 = 174^\circ$$

$$\text{Iteration yields } \omega \approx 1.1 \times 10^5 \text{ rad/s}$$

$$\text{For oscillations: } |AB(\omega_{180})| \geq 1$$

$$\frac{\beta \cdot 10^3}{(\sqrt{1 + 11^2})(\sqrt{1 + 1.1^2})} \geq 1$$

$$\Rightarrow \beta \geq 0.0244$$

Section 8.9

Effect of Feedback on Amplifier Poles

8.65

$$A(jf) = \frac{(10 \times 10^6)/10^4}{1 + jf/10^4}$$

$$\therefore A(jf) = \frac{10^3}{1 + jf/10^4}$$

$\beta = 0.1$ independent of frequency

$$A_f(jf) = \frac{10^3}{1 + 10^3(0.1)} \cdot \frac{1}{1 + \frac{jf}{10^4(1 + 10^3(0.1))}}$$

$$= \frac{9.9}{1 + jf/(101 \times 10^4)}$$

$$A_f(0) = 9.9 \text{ V/V}$$

$$f_{pf} = 10^4(101) = 1.01 \text{ MHz}$$

$$\text{for } \frac{f}{f_{pf}} \gg 1: A_f \approx 9.9 \frac{10^4(101)}{f}$$

$$\text{for } A_f = 1: f = f_T = 10 \text{ MHz}$$

Pole is shifted by $(1 + A(0)\beta) = 101$

8.66

$$A(jf) = \frac{10^3}{(1 + jf/10^4)(1 + jf/10^5)}$$

(a) closed-loop poles given by

$$1 + A(s)B = 0$$

using $p = jf$

$$p^2 + p(10^4 + 10^5) + (1 + 10^3\beta)10^4 \cdot 10^5 = 0$$

$$\text{i.e. } p^2 + (1.1 \times 10^5)p + 10^9(1 + 10^3\beta) = 0$$

compare terms with

$$(p + f_{pf})^2 = p^2 + 2f_{pf} \cdot p + f_{pf}^2$$

$$2f_{pf} = (1.1 \times 10^5)$$

$$(1 + 10^3\beta) \times 10^9 = f_{pf}^2$$

$$\Rightarrow f_{pf} = 5.5 \times 10^5$$

$$\text{and } (1 + 10^3\beta) = 3.025 \Rightarrow \beta = 2.025 \times 10^{-3}$$

$$(b) A_f(0) = \frac{10^3}{1 + 10^3(2.025 \times 10^{-3})} = 330.6\%$$

$$(c) 55 \text{ kHz}: |A(s)B| = 1$$

$$\Rightarrow A_f(55 \text{ kHz}) = \frac{A_f(0)}{(1 + |AB|)} \approx 165.3 \text{ V/V}$$

(c) from $s^2 + (\omega_0/Q)s + \omega_0^2$ cf. above

$$Q = \frac{f_{pf}}{2f_{pf}} = \frac{1}{2}$$

$$(d) p^2 + 1.1 \times 10^5 p + (1 + 10^3\beta) = 0$$

$$\Rightarrow p^2 + 1.1 \times 10^5 p + 21.25 \times 10^9 = 0$$

$$p = \frac{-1.1 \times 10^5 \pm \sqrt{(1.1 \times 10^5)^2 - 4(1)(21.25 \times 10^9)}}{2}$$

$$= \frac{-1.1 \times 10^5 \pm j 2.7 \times 10^5}{2}$$

$$= -5.5 \times 10^4 \pm j 1.35 \times 10^5 \text{ Hz}$$

$$Q = \frac{|P|}{2(5.5 \times 10^4)} = \frac{\sqrt{(5.5 \times 10^4)^2 + (1.35 \times 10^5)^2}}{1.1 \times 10^5}$$

$$= 1.33$$

8.67

$$A(jf) = \frac{10^3}{(1 + jf/10)(1 + jf/f_p)}$$

$$A_f(0) = \frac{10^3}{1 + 10^3\beta} = 100$$

$$\Rightarrow \beta = 9 \times 10^{-3} \text{ V/V}$$

Maximally flat when $Q = 0.707 = 1/\sqrt{2}$ from

$$p^2 + p(f_1 + f_2) + (1 + A_0\beta)(f_1 \times f_2) = 0$$

$$Q = \frac{\sqrt{(1 + A_0\beta)f_1 f_2}}{f_1 + f_2}$$

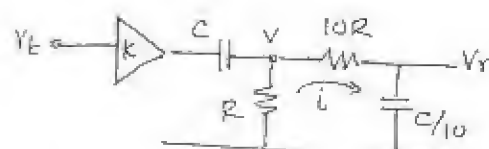
$$\Rightarrow \frac{\sqrt{(1 + 10^3\beta)10^3 f_{pf}}}{10^3 + f_{pf}} = \frac{1}{\sqrt{2}}$$

$$\Rightarrow f_{pf}^2 + (2 \times 10^3)f_{pf} + 10^6 = 2(1 + 10^3\beta)10^6$$

$$\Rightarrow f_{pf} = \frac{18 \times 10^3 \pm \sqrt{(18 \times 10^3)^2 - 4(10^6)}}{2}$$

$$= 17.94 \text{ kHz}$$

8.68



$$i = \frac{SCV_r}{10} \Rightarrow V \neq V_r + SCRV_r$$

$$= V_r(1 + SCR)$$

By KCL: $\sum i = 0$ at V

$$\Rightarrow \frac{(KV_t - V)}{1/sC} = \frac{V}{R} + i = \frac{V}{R} + \frac{sCV_r}{10}$$

$$KsCV_t - sCV_r(1+sCR) = \frac{V}{R} \\ = V_r \left(\frac{1+sCR}{R} + \frac{sC}{10} \right)$$

Collecting terms:

$$\frac{K}{10} sCV_t R = V_r \left[(sCR)^2 + 2.1sCR + 1 \right]$$

$$\text{Thus } L(s) \triangleq -V_r/V_t \\ = \frac{-K/CR s}{s^2 + \frac{2.1s}{CR} + \frac{1}{CR^2}} \\ \equiv \frac{-K/CR s}{s^2 + \left(\frac{\omega_0}{Q}\right)s + \omega_0^2}$$

from which $\omega_0 = 1/CR$
 $Q = \frac{1}{2.1-K}$

poles coincide when $Q = 1/2$
 $\Rightarrow K = 2.1 - 2 = 0.1$

maximally flat when $Q = 1/\sqrt{2}$
 $\Rightarrow K = 2.1 - 1.414 = 0.686$

oscillates when $Q \rightarrow \infty$
 $\Rightarrow K = 2.1$

8.69

$$A(jf) = \frac{K}{1+jf/10^7}$$

for $\beta=1$: $A\beta = \frac{K^3\beta}{(1+jf/10^7)^3} = \frac{K^3}{(1+jf/10^7)^3}$

For oscillations:

$$|A\beta| \geq 1 \text{ at } \angle(A\beta) = 180^\circ$$

i.e. $+3 \tan^{-1} \left(\frac{f}{10^7} \right) = 60^\circ$

$$\Rightarrow f_{180} = \sqrt{3} \times 10^7 \text{ Hz}$$

$$\therefore \left[\frac{K}{\sqrt{1+(f/10^7)^2}} \right]^3 \geq 1 \Rightarrow K \geq 2$$

$$f_{osc} = f_{180} = 17.3 \text{ MHz.}$$

Section 8.10

Stability Study using Bode Plots

8.70

$$A(f) = \frac{10^5}{1+jf/10}$$

for $\beta=1$: $A(f)\beta = \frac{10^5}{1+jf/10}$

for $f \gg 10$: $|A\beta| \approx 10^5 \cdot \frac{10}{f}$

$$\Rightarrow f_1 = 1 \text{ MHz}$$

at f_1 : phase margin $= 180^\circ - \tan^{-1} \frac{10^6}{10}$
 $= 90^\circ$

8.71

$$A(f) = \frac{10^5}{(1+jf/10)(1+jf/10^4)}$$

$$A\beta(0) = 10^5\beta$$

$$A_f(0) = 180 = \frac{10^5}{1+10^5\beta} \Rightarrow \beta \approx 0.01$$

$$|A\beta|=1 \Rightarrow |1+jf/10| \cdot |1+jf/10^4| = 10^5\beta = 10^3$$

$$(1+f^2/10^2)(1+f^2/10^8) = 10^6$$

$$f^4 + f^2(10^8 + 10^2) - (10^8)(10^2)10^6 = 0$$

$$f^2 \approx \frac{-10^8 + \sqrt{10^{16} + 4 \times 10^6}}{2}$$

$$\Rightarrow 61.8 \times 10^6 \Rightarrow f = 7.86 \text{ kHz}$$

Phase margin

$$= 180 - \left(\tan^{-1} \frac{7.86 \times 10^3}{10} + \tan^{-1} \frac{7.86}{10^4} \right) \\ \approx 180 - 90^\circ - 38.16^\circ = 51.8^\circ$$

For PM $\geq 45^\circ$: $\tan^{-1} f/10^4 \leq 45^\circ$

$$\Rightarrow f_1 \leq 10^4$$

thus

$$|A\beta|=1 = \frac{10^5\beta}{\sqrt{(1+(f/10)^2)} \cdot \sqrt{2}}$$

$$\Rightarrow \beta = \sqrt{2}/100 = 0.0141$$

8.72

$$\begin{aligned}
 |1 + e^{-j\theta}| &= |1 + \cos\theta - j\sin\theta| \\
 &= [(1 + \cos\theta)^2 + (\sin\theta)^2]^{1/2} \\
 &= [1 + 2\cos\theta + \cos^2\theta + 1 - \cos^2\theta]^{1/2} \\
 &= \sqrt{2} (1 + \cos\theta)^{1/2}
 \end{aligned}$$

for 5%: $1 + \cos\theta = \frac{1}{1.05^2(2)} = 0.9535$

$\theta = 123.13^\circ$ and $PM = 180 - \theta = 56.87^\circ$

for 10%: $1 + \cos\theta = \frac{1}{1.1^2(2)} = 0.586$

$\theta = 125.43^\circ$ and $PM = 54.07^\circ$

for 0.1 dB: $10^{0.1/20} = 1.0116$

$\cos\theta = \frac{1}{2(1.0116)^2} - 1 = -0.5114$

$\theta = 120.76^\circ$ and $PM = 59.24^\circ$

for 1 dB: $10^{1/20} = 1.122$

$\cos\theta = \frac{1}{2(1.122)^2} - 1 = -0.6028$

$\theta = 127.07^\circ$ and $PM = 52.93^\circ$

8.73

$$A(jf) = \frac{10^5}{(1 + j\frac{f}{10^5})(1 + j\frac{f}{3.16 \times 10^5})(1 + j\frac{f}{10^6})}$$

Assume β independent of frequency

For 45° PM: $\theta = 180 - 45$

$$\tan^{-1} \frac{f_1}{10^5} + \tan^{-1} \frac{f_1}{3.16 \times 10^5} + \tan^{-1} \frac{f_1}{10^6} = 135^\circ$$

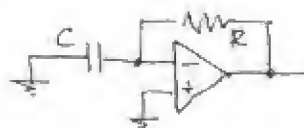
Solve $\Rightarrow f_1 = 3.16 \times 10^5$ Hz

$$|A\beta(f_1)| = 1 = \frac{10^5 \beta}{\sqrt{1 + (3.16)^2} \cdot \sqrt{2} \cdot \sqrt{1 + (0.316)^2}}$$

$\Rightarrow \beta = 49 \times 10^{-6}$

$$A_f(0) = \frac{10^5}{1 + 10^5(4.9 \times 10^{-6})} = 16.9 \times 10^3$$

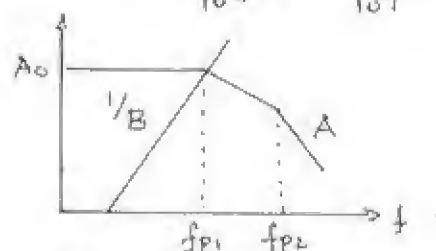
8.74



$$\beta = \frac{1/sC}{R + 1/sC} = \frac{1}{1 + sCR}$$

$$\beta(f) = \frac{1}{1 + j2\pi fCR}$$

$$A(jf) = \frac{10^3}{(1 + j\frac{f}{10^4})(1 + j\frac{f}{10^7})}$$



From sketch, we need

$$A_0 \frac{1}{2\pi f_{P1}CR} = 1 = A\beta$$

$$\Rightarrow RC = \frac{A_0}{2\pi f_{P1}} = \frac{10^3}{2\pi \times 10^6} = 159.2 \mu s$$

At 1 MHz $\text{Ang}(\beta) = -90^\circ$

$$\text{Ang}(A) = -\tan^{-1} 1 - \tan^{-1} 0.1 = -45 - 5.7 = -50.7^\circ$$

$\therefore PM = 180 - (90 + 50.7) = 39.3^\circ$

Gain margin exists at ω_{180}

Then $\tan^{-1} \frac{f_1}{10^4} + \tan^{-1} \frac{f_1}{10^7} = 90^\circ$

$\therefore f_{180} = \sqrt{10^4 \cdot 10^7} = \text{geometric mean} = 3.16 \text{ MHz}$

$$|A\beta(f_{180})| = 20 \log |A| - 20 \log |\beta|$$

|A| has fallen 10 dB, $|\beta|$ has risen 10 dB

Thus $GM = +10 - (-10) = 20 \text{ dB}$

8.75

For 90° PM:

$$\tan^{-1} \frac{f_1}{10^5} + \tan^{-1} \frac{f_1}{10^6} + \tan^{-1} \frac{f_1}{10^7} = 90^\circ$$

From graph $f_1 = 3 \times 10^5 \text{ Hz}$
 Thus $71.6 + 16.7 + 1.72 = 89.9^\circ$ (close)
 $|A(f_1)| = \frac{10^5}{\sqrt{1+3^2} \cdot \sqrt{1+0.3^2} \cdot \sqrt{1+0.3^2}} = 30.28 \times 10^3$
 $|AB| = 1 \Rightarrow \beta = 33.0 \times 10^{-6}$
 $\therefore A_f(0) = \frac{10^5}{1+10^5 \beta} = 2.32 \times 10^4$

For $\text{PM} = 45^\circ$ $f_1 \approx 10^6 \text{ Hz}$ from graph
 Thus $84.3 + 45 + 5.7 = 135^\circ$ (ok)
 $|A(f_2)| = \frac{10^5}{\sqrt{1+10^2} \cdot \sqrt{2} \cdot \sqrt{1+0.1^2}} = 7 \times 10^3$
 $|AB| = 1 \Rightarrow \beta = 1.43 \times 10^{-4}$
 $\therefore A_f(0) = \frac{10^5}{1+10^5 \beta} = 6.54 \times 10^3$

Section 8.11 Frequency Compensation

8.76

$f_1 = 2 \text{ MHz}$
 $A_0 = 80 \text{ dB} \approx 10^4$
 $\Rightarrow f_p = f_1 / A = (2 \times 10^6) / 10^4 = 200 \text{ Hz}$

8.77

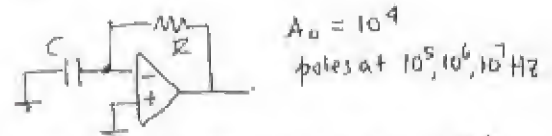
$f_{p1} = 2 \text{ MHz}$, $f_{p2} = 10 \text{ MHz}$
 $A_0 = 80 \text{ dB} \approx 10^4$
 $f_b = \frac{f_p}{A_0} = \frac{10 \times 10^6}{10^4} = 10^3 \text{ Hz}$
 $f_b' = 1 / (C_1 + C_2) 2\pi R_1 \Rightarrow C \times \frac{2 \times 10^6}{10^3} = 2000 C$

8.78

$\omega_{p1} = \frac{1}{10CR}$, $\omega_{p2} = \frac{1}{CR}$
 $\omega_{p1}' \approx \frac{1}{g_m R_2 C_f R_1} = \frac{1}{\frac{100}{R} \cdot R \cdot C_f R} = \frac{1}{100 C_f R}$
 $\omega_{p2}' \approx \frac{g_m C_f}{C_2 + C_f(C_1 + C_2)} = \frac{g_m C_f}{C_1(C_2 + C_f) + C_f C_2}$
 for $C_f \gg C_2 = C$

$$\omega_{p2}' \approx \frac{g_m}{C_1 + C_2} = \frac{100}{R(C_1 + C_2)} = \frac{9.1}{CR}$$

8.79



For $\beta = 1$, f_p must be kept $\times 10^4$
 lower than lowest amplifier pole at 10^5 Hz
 $\Rightarrow f_p = \frac{10^5}{10^4} = 10 \text{ Hz}$
 $f_p = \frac{1}{2\pi CR}$ and $R = 1 \text{ M}\Omega$
 $\Rightarrow C = \frac{1}{2\pi \cdot 10^6 (10)} = 15.9 \text{ nF}$

8.80

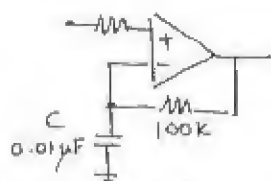
$A_0 = 80 \text{ dB} \approx 10^4$
 $f_{p1} = 10^5 = \frac{1}{2\pi C_1 R_1} \Rightarrow R_1 = \frac{1}{2\pi f_{p1} C_1}$
 $\Rightarrow R_1 = \frac{1}{2\pi \cdot 10^5 (150 \times 10^{-12})} = 10.62 \text{ k}\Omega$
 $f_{p2} = 10^6 = \frac{1}{2\pi C_2 R_2}$
 $\Rightarrow R_2 = \frac{1}{2\pi \cdot 10^6 (5 \times 10^{-12})} = 31.85 \text{ k}\Omega$

Assuming $f_{p2}' \gg f_{p3}$
 $f_{p1}' = \frac{f_{p3}}{10^4} = \frac{2 \times 10^6}{10^4} = 200 \text{ Hz}$

and $f_{p1}' = \frac{1}{2\pi g_m R_1 R_2 C_f} \Rightarrow C_f = \frac{1}{2\pi g_m R_1 R_2 f_{p1}'}$

$\therefore C_f = \frac{1}{2\pi (40 \times 10^{-3}) (10.62 \times 10^3) (31.85 \times 10^3) 200}$
 $= 58.8 \text{ pF}$

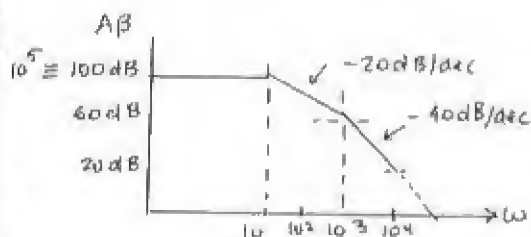
$f_{p2}' = \frac{1}{2\pi} \frac{g_m C_f}{C_1 C_2 + C_f(C_1 + C_2)}$
 $= \frac{1}{2\pi} \frac{40 \times 10^{-3} (58.8 \times 10^{-12})}{(150 \times 5) 10^{-24} + 58.8 (155) 10^{-24}} = 38.6 \text{ MHz}$



$$\beta(s) = \frac{1}{1 + sCR}$$

$$= \frac{1}{1 + 10^{-3}s}$$

$$10) AB(s) = \frac{10^5}{1 + s/10} \cdot \frac{1}{1 + s/10^3}$$



- 1b) From plot $(A_{p1}) = 20 \text{ dB}$ at $10^4 \approx \omega$
Hence $|AB| = 1$ at 31.6 Krad/s ($\frac{1}{2} \text{ dec}$)

$$1c) A_f(s) = \frac{10^5}{1 + s/10}$$

$$1 + \frac{10^5}{1 + s/10} \cdot \frac{1}{1 + s/10^3}$$

$$= \frac{10^5(1 + s/10^3)}{(1 + s/10)(1 + s/10^3) + 10^5}$$

$$\therefore A_f(s) = \frac{1 + s/10^3}{1 + s/10^6 + s^2/10^9} = \frac{10^6 s + 10^9}{s^2 + 10^2 s + 10^9}$$

Zero at $s = -10^3 \text{ rad/s}$

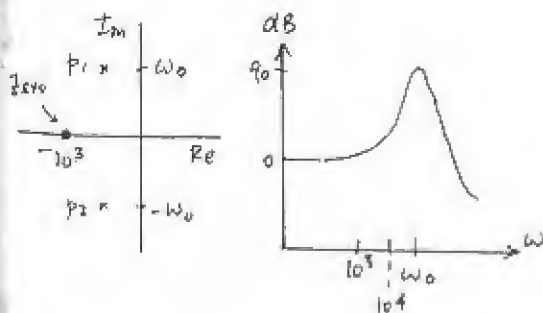
Poles at $\frac{-10^3 \pm \sqrt{10^6 - 4 \times 10^9}}{2}$

$$= \frac{-10^3 \pm j 63.2 \times 10^3}{2}$$

$$= -500 \pm j 31.6 \times 10^3 \text{ rad/s}$$

$$\omega_0 = 31.6 \text{ Krad/s}$$

$$Q = 31.6$$



Chapter 9 - Problems

Section 9.1: The two-stage CMOS op. Amp

9.1

$$\begin{aligned} V_{icm(max)} &\leq V_{DD} - |V_{tp}| - |V_{ov1}| - |V_{ov5}| \\ &\leq +2.5 - 0.7 - 0.3 - 0.3 \\ &\leq +1.2V \end{aligned}$$

$$\begin{aligned} V_{icm(min)} &\geq -V_{SS} + V_{ov3} + V_{tn} - |V_{tp}| \\ &\geq -2.5 + 0.3 (+0.7 - 0.7) \\ &\geq -2.2V \end{aligned}$$

$$\begin{aligned} -V_{SS} + V_{ov6} &\leq V_0 \leq V_{DD} - |V_{ov7}| \\ -2.5 + 0.3 &\leq V_0 \leq +2.5 - 0.3 \\ -2.2V &\leq V_0 \leq +2.2V \end{aligned}$$

9.2

$$\begin{aligned} V_A' &= 2.5V/\mu m, |V_P'| = 2.0V/\mu m, L = 0.8\mu m \\ \text{Hence } V_A &= 20V \text{ and } |V_P| = 16V \\ \text{For all devices } V_{ov} &= 0.25V \end{aligned}$$

$$\begin{aligned} A &= A_1 A_2 = G_{m1}(r_{o2} || r_{o4}) G_{m2}(r_{o6} || r_{o7}) \\ [r_{o2} || r_{o4}] &= \left[\frac{V_A}{I} \times \frac{V_P}{I} \right] \times \frac{I}{V_A + V_P} = \left[\frac{V_A V_P}{I} \right] \end{aligned}$$

$$\text{For } A_2: R_o = \frac{8.89}{I} \rightarrow \frac{8.89V}{0.4mA} = 22.2k\Omega$$

To avoid systematic output d.c. offset

$$\frac{(W/L)_6}{(W/L)_4} = \frac{2(W/L)_7}{(W/L)_5}$$

Since Q_5, Q_6, Q_7 carry I and Q_4 only $I/2$
satisfy requirement by making Q_4 have $(W/2)/2$

$$\text{Since } g_{m1} = \sqrt{2(\mu C_{ox})(W/L)I} = 2K(V_{ov})$$

$$g_{m1} = 2I_1/V_{ov} = 0.4mA/0.25V = 1.6mA/V$$

$$g_{m6} = 2I_6/V_{ov} = 3.2mA/V$$

$$\therefore A = (1.6 \times 44.4)(3.2)(22.2) = 5047V/V$$

For unity gain amplifier

$$A_F = \frac{A}{1+A\beta} = \frac{5047}{1+5047\beta} = 1$$

$$\text{Thus } (1+A\beta) = 5047$$

$$\begin{aligned} \text{Then } R_{of} &= R_o / (1+A\beta) \\ &= 22.2k / 5047 \approx 4.4\Omega \end{aligned}$$

9.3

$$\begin{aligned} A &= A_1 A_2 = G_{m1}(r_{o2} || r_{o4}) G_{m2}(r_{o6} || r_{o7}) \\ &= \frac{2I_1}{V_{ov}} \cdot \frac{1}{2} \frac{V_A}{I_1} \cdot \frac{2I_2}{V_{ov}} \cdot \frac{1}{2} \frac{V_A}{I_2} \\ &= \left[\frac{V_A}{V_{ov}} \right]^2 = 2500 \end{aligned}$$

$$\text{Where } V_A = 10V/\mu m \times 1\mu m = 10V$$

$$\text{Hence } V_{ov} = V_A / 50 = 10/50 = 0.2V$$

9.4

$$\begin{aligned} \text{From } \frac{(W/L)_6}{(W/L)_4} &= \frac{2(W/L)_7}{(W/L)_5} \\ (W/L)_6 &= \frac{2(60/0.5)(10/0.5)}{(60/0.5)} \end{aligned}$$

$$I_{D_P} = \frac{1}{2} [60] (W/L) (V_{GS} - V_T)^2$$

$$\begin{aligned} \text{Given } I_{ref} &= 225\mu A = \frac{1}{2} 60 (60/0.5) [V_{ov}]^2 \\ \Rightarrow V_{ov} &= 15/60 = 0.25V \end{aligned}$$

$$\text{Given } V_T = 0.75V$$

$$\Rightarrow V_{GS} = V_T + V_{ov} = 0.25 + 0.75 = 1V$$

Since Q_5, Q_7, Q_8 have same (W/L)

$$\Rightarrow I_1 = I_2 = I_3 = I_4 = \frac{1}{2} I_5 = \frac{1}{2} I_8$$

$$\text{For } Q_2: I_1 = \frac{1}{2} 60 (30/0.5) (V_{ov})^2 = 112.5\mu A$$

$$\Rightarrow V_{ov1} = 0.25V$$

$$\Rightarrow V_{GS1} = V_T + V_{ov1} = 1.0V$$

$$\text{For } Q_3 \text{ and } Q_4: I_3 = \frac{1}{2} 180 (10/0.5) (V_{ov})^2 = 112.5\mu A$$

$$\Rightarrow V_{ov3} = 0.25V$$

$$\Rightarrow V_{GS3} = 0.25 + 0.75 = 1V$$

$$\text{For } Q_6: I_6 = \frac{1}{2} 180 (20/0.5) (V_{ov})^2 = 225\mu A$$

$$\Rightarrow V_{ov6} = 0.35V$$

$$\Rightarrow V_{GS6} = 0.35 + 0.75 = 1.1V$$

$$r_o = \frac{V_A}{I} = \frac{9V}{I} \text{ mA} \quad \text{and } |V_A| = 9V$$

$$g_m = \frac{2I}{V_{ov}}$$

and $|V_{ov}|$ vary

Q	K ($\mu\text{A/V}^2$)	I (μA)	V_{OV} (V)	V_{GS} (V)	g_m (mA/V)	r_o (k Ω)
Q1	60	112.5	0.25	0.81	0.9	80
Q2	60	112.5	0.25	0.81	0.9	80
Q3	180	180	0.25	1.0	0.9	80
Q4	180	180	0.25	1.0	0.9	80
Q5	60	225	0.25	1.0	1.8	40
Q6	180	225	0.35	1.1	1.285	40
Q7	60	60	0.25	1.0	1.8	40
Q8	60	60	0.25	1.0	1.8	40

$$A_1 = G_{m1}(r_{o2} \parallel r_{o4}) = 0.9 \times 40 = 36 \text{ V/V}$$

$$A_2 = G_{m6}(r_{o6} \parallel r_{o7}) = 1.285 \times 20 = 25.7 \text{ V/V}$$

$$A = A_1 A_2 = 36 \times 25.7 = 925 \text{ V/V}$$

$$V_{ICM(max)} \leq V_{DD} - |V_{tp}| - |V_{ov1}| - |V_{ov5}|$$

$$\leq 1.5 - 0.75 - 0.25 - 0.25$$

$$\leq +0.25 \text{ V}$$

$$V_{ICM(min)} \geq -V_{SS} + V_{ov3} + V_{ov7} - |V_{tp1}|$$

$$\geq -1.5 + 0.25 = -1.25 \text{ V}$$

$$-V_{SS} + V_{ov6} \leq V_0 \leq +V_{DD} - |V_{ov7}|$$

$$-1.5 + 0.35 \leq V_0 \leq +1.5 - 0.25$$

$$-1.15 \text{ V} \leq V_0 \leq +1.25 \text{ V}$$

9.5

$$G_{m1} = 0.3 \text{ mA/V} \quad G_{m2} = 0.6 \text{ mA/V} \quad C_2 = 1 \text{ pF}$$

$$r_{o2} = r_{o4} = 222 \text{ k}\Omega \quad r_{o6} = r_{o7} = 111 \text{ k}\Omega$$

$$(a) f_{p2} = \frac{G_{m2}}{2\pi C_2} = \frac{0.6 \times 10^{-3}}{2\pi \times 10^{-12}} = 95.5 \text{ MHz}$$

$$(b) R = \frac{1}{G_{m2}} = \frac{1}{0.6} = 1.66 \text{ k}\Omega$$

$$(c) \text{ For } PM = 90^\circ: \tan^{-1} \frac{f_t}{f_{p2}} = 10^\circ$$

$$f_t = f_{p2} \tan 10^\circ$$

$$= 95.5 \times 0.176 = 16.84 \text{ MHz}$$

$$C_c = \frac{G_{m1}}{2\pi f_t} = \frac{0.3 \times 10^{-3}}{2\pi \times 16.84 \times 10^6} \Rightarrow 2.83 \text{ pF}$$

$$A = A_1 A_2 = G_{m1}(r_{o2} \parallel r_{o4}) G_{m2}(r_{o6} \parallel r_{o7})$$

$$= 0.3 \times 111 \times 0.6 \times 55.5$$

$$= 1109 \approx 60.8 \text{ dB}$$

$$\text{Dominant pole } f_{p1} = f_t / |A|$$

Thus f_{p1} is approx 3 decades below f_t
 i.e. at 16.84 KHz providing uniform
 20 dB/dec slope down to f_t .

$$(d) f_t = \frac{G_{m1}}{2\pi C_c} \quad \therefore \text{to double } f_t, \text{ halve } C_c$$

$$C_{c(new)} = 1.4 \text{ pF}$$

$$\tan^{-1} \frac{f_t}{f_p} = \tan^{-1} \frac{33.7}{95.5} = 19.4^\circ$$

The zero must be moved to reduce
 the $19.4 - 10 = 9.4^\circ$

$$\tan^{-1} \frac{f_t}{f_z} = 9.4^\circ \Rightarrow \frac{f_t}{f_z} = 0.16$$

$$\Rightarrow f_z = 0.16 f_t = 0.16 \times 33.7$$

$$= 5.6 \text{ MHz}$$

$$f_z = \frac{1}{2\pi C_c [R - \frac{1}{G_{m1}}]} \Rightarrow [R - \frac{1}{G_{m1}}] = \frac{1}{2\pi f_z C_c}$$

$$\text{Hence } [R - \frac{1}{G_{m1}}] = \frac{10^{12} \cdot 10^{-6}}{2\pi \times 5.6 \times 1.4}$$

$$R = 1.67 + 20.3 = 21.97 \text{ k}\Omega$$

9.6

Two-stage amp with $C_2 = 1 \text{ pF}$

$$f_t = 100 \text{ MHz}, PM = 75^\circ$$

$$\text{For } PM = 75^\circ: \tan^{-1} \frac{f_t}{f_{p2}} = 15^\circ$$

$$\therefore f_{p2} = f_t \tan 15^\circ = 3.73 f_t = 373 \text{ MHz}$$

$$f_{p2} = \frac{G_{m6}}{2\pi C_2} = \frac{1}{2\pi R_2 \times 10^{-12}} = 373 \text{ MHz}$$

$$\Rightarrow R_2 = \frac{10^{12}}{2\pi (373 \times 10^6)} = 426 \Omega$$

$$\Rightarrow G_{m6} = \frac{1}{R_2} = 2.35 \times 10^{-3} \text{ mA/V}$$

To move zero to infinity $R = \frac{1}{G_{m6}} = 426 \Omega$

$$SR = \frac{I}{C_c} = \frac{200 \mu\text{A}}{C_c}$$

$$SR = 2\pi f_t V_{ov1} = 2\pi \times 10^8 \times 0.2 = 1.26 \times 10^8 \text{ V/s}$$

$$\Rightarrow C_c = \frac{200 \times 10^{-6}}{1.26 \times 10^8} \Rightarrow 1.6 \text{ pF}$$

9.7

$$G_{m1} = 1 \text{ mA/V}, G_{m2} = 2 \text{ mA/V}, R = 500 \Omega$$

$$f_t \approx \frac{G_{m1}}{2\pi C_c} \Rightarrow C_c = \frac{G_{m1}}{2\pi f_t} = \frac{1 \times 10^{-3}}{2\pi \cdot 100 \times 10^6} \Rightarrow 1.59 \text{ pF}$$

$$\text{For } \frac{1}{G_{m2}} - R = \frac{10^3}{2} - 500 = 0$$

Zero has been moved to ∞

$$\text{For PM} = 60^\circ: f_t = f_{p2} \tan(90 - 30)^\circ$$

$$\Rightarrow f_{p2} = f_t / \tan 30^\circ = 173 \text{ MHz}$$

$$C_2 \approx \frac{G_{m2}}{2\pi f_{p2}} = \frac{2 \times 10^{-3}}{2\pi \cdot 173 \times 10^6} = 1.84 \text{ pF}$$

9.8

$$SR = 60 \text{ V}/\mu\text{s} \quad f_t = 50 \text{ MHz}$$

$$(a) SR = 2\pi f_t V_{ov1}$$

$$\Rightarrow V_{ov1} = SR / 2\pi f_t = \frac{60 \times 10^6}{2\pi (50 \times 10^6)} \approx 0.2 \text{ V}$$

$$(b) SR = \frac{I}{C_c} \Rightarrow C_c = \frac{100 \mu\text{A}}{60 \times 10^6} = 1.67 \text{ pF}$$

$$(c) I = \frac{1}{2} \mu C_{ox} (W/L) [V_{ov}]^2 \Rightarrow \left(\frac{W}{L}\right) = \frac{2I}{50 (0.2)^2} = \frac{100}{1}$$

9.9

Invert circuit leaving V_{DD} & V_{SS} and reverse all arrows on FETs.

Section 9.2

The Folded-Cascode OP AMP

9.10

From circuit: Current drawn from V_{DD} rail
 $= 2 I_B = \text{Current returned to } V_{SS} \text{ rail}$

$$\therefore \text{Power} = (V_{DD} + V_{SS}) \times 2 I_B \Rightarrow 1 \text{ mW} = (1.65 + 1.65) \times 2 I_B$$

$$\therefore I_B = \frac{1 \text{ mW}}{4 \times 1.65 \text{ V}} = 151.5 \mu\text{A}$$

$$\Rightarrow I = I_B / 1.2 = 126.3 \mu\text{A}$$

9.11

V_{BIAS1} : V_S can rise to $V_{DD} + V_T - V_{ov}$
 V_{D3} can rise to $V_{S3} - V_{ov}$

$$\therefore V_{BIAS1} = V_{DD} - V_{ov10} - V_{ov4} + V_T = 1.65 - 0.2 - 0.2 + 0.5 = 1.75 \text{ V}$$

$$V_{BIAS2} = V_{DD} - V_{ov10} = +1.65 - 0.2 = +1.45 \text{ V}$$

$$V_{BIAS3} = -V_{SS} + V_{ov11} = -1.65 + 0.2 = -1.45 \text{ V}$$

$$V_{ICM(max)} = V_{DD} - |V_{ov9}| + V_{Tn} = +1.65 - 0.2 + 0.5 = +1.75 \text{ V}$$

$$V_{ICM(min)} = -V_{SS} + V_{ov11} + V_{ov1} + V_T = -1.65 + 0.2 + 0.2 + 0.5 = -0.75 \text{ V}$$

$$-V_{SS} + 2V_{ov} + V_T \leq V_0 \leq +V_{DD} - 2V_{ov} \\ -1.65 + 0.4 + 0.5 \leq V_0 \leq +1.65 - 0.4 \\ -0.75 \text{ V} \leq V_0 \leq +1.25 \text{ V}$$

9.12

$$I = 125 \mu\text{A}, I_B = 150 \mu\text{A}, V_T = 0.2 \text{ V}$$

$$\text{For } Q_9, Q_{10}: I_B = 150 \mu\text{A}$$

$$I = \frac{1}{2} (\mu C_{ox}) (W/L) (V_{ov})^2$$

$$150 = \frac{1}{2} \cdot 90 (W/L) (0.2)^2$$

$$\Rightarrow (W/L)_{9,10} = (83.33/1)$$

$$\text{For } Q_1, Q_2: I = 125 \mu\text{A} / 2$$

$$\frac{1}{2} \cdot 125 = \frac{1}{2} \cdot 250 (W/L) (0.2)^2$$

$$\Rightarrow (W/L)_{1,2} = (12.5/1)$$

$$\text{For } Q_{11}: I = 125 \mu A$$

$$125 = \frac{1}{2} 250 (W/L) (0.2)^2$$

$$\Rightarrow (W/L)_{11} = (25/1)$$

$$\text{For } Q_3, Q_4: I = 125 \mu A/2$$

$$\frac{1}{2} 125 = \frac{1}{2} 50 (W/L) (0.2)^2$$

$$\Rightarrow (W/L)_{3,4} = (52/1)$$

$$\text{For } Q_5, Q_6, Q_7, Q_8: I = 125 \mu A/2$$

$$\frac{1}{2} 125 = \frac{1}{2} 250 (W/L) (0.2)^2$$

$$\Rightarrow (W/L)_{5,6,7,8} = (12.5/1)$$

9.13

$$(1) SR = \frac{I}{C_L} \Rightarrow I = SR \times C_L = 10 \times 10^6 \times 10 \times 10^{-12} = 100 \mu A$$

$$(2) I_B = 1.2 I = 120 \mu A$$

$$(3) f_p = \frac{1}{2\pi C_L R_v} \quad f_t = \frac{G_m}{2\pi C_L}$$

$$G_m = \frac{2I/2}{V_{ov}} = \frac{100 \mu A}{0.2 V} = 0.5 mA/V$$

$$f_t = \frac{0.5 \times 10^{-3}}{2\pi \times 10 \times 10^{-12}} = 7.96 MHz$$

$$(4) R_{of} \approx \frac{1}{G_m} = \frac{1000}{0.5} = 2 k\Omega$$

$$A_v = f_t/f_p = G_m R_o$$

$$\text{But } R_{of} = \frac{R_o}{1+G_m R_o} \Rightarrow R_o = 2 M\Omega$$

$$\therefore A_v = 0.5 \times 10^{-3} \times 2 \times 10^6 = 1000$$

$$f_p = f_t/1000 = 7.96 kHz$$

$$(5) \theta = -\tan^{-1} \frac{f_t}{f_p} - 2(\tan^{-1} \frac{f_t}{f_p})$$

$$PM @ f_{p2} = 90^\circ - \tan^{-1} \frac{f_t}{f_{p2}}$$

$$= 90^\circ - \tan^{-1} \left[\frac{7.96 MHz}{25 MHz} \right]$$

$$= 90^\circ - 17.7^\circ = 72.3^\circ$$

$$(6) \text{ For } PM = 75^\circ: \tan^{-1} \frac{f_t}{f_{p2}} = 15^\circ$$

$$\text{Thus } f_t^* = f_{p2} \tan 15^\circ = 25 MHz \times 0.27 = 6.7 MHz$$

$$\frac{f_t^*}{f_t} = \frac{C_L}{C_L^*} \Rightarrow \frac{6.7}{7.96} = \frac{10 pF}{C_L^*}$$

$$\Rightarrow C_L^* = C_L \frac{7.96}{6.7} = C_L \times 1.19$$

\therefore Increase C_L by 19%.

$$(7) SR^* = \frac{I}{C_L^*} \Rightarrow \frac{SR}{1.19} = 8.4 V/\mu s$$

9.14

$$G_m = \frac{I}{V_{ov}} \quad r_o = \frac{V_A}{I}$$

$$R_o = R_{o4} \parallel R_{o6}$$

$$R_{o4} = g_{m4} r_{o4} (r_{o2} \parallel r_{o10})$$

$$R_{o6} = g_{m6} (r_{o6} \parallel r_{o8})$$

$$A = G_m R_o$$

$$Q_{10}: I = I_B \Rightarrow g_{m10} = 0.75 mA/V$$

$$r_{o10} = 66.6 k\Omega$$

$$Q_x: I = 125 \mu A \Rightarrow g_x = 0.31 mA/V$$

$$r_{ox} = 160 k\Omega$$

$$\therefore R_{o4} = 0.31 \times 160 \times 47k = 235 k\Omega$$

$$R_{o6} = 0.31 \times 160 \times 160k = 8000 k\Omega$$

$$R_o = 235 \parallel 8000 = 1.8 M\Omega$$

$$A = g_m R_o = 0.31 \times 1800 = 558$$

$$\frac{V_o}{V_i} = 1 + \frac{(1/sC)}{(1/s9C)} = 1 + \frac{9sC}{sC} = 10$$

$$\therefore \beta = 1/10 = 0.1$$

$$A_F = \frac{A}{1+A\beta} = \frac{558}{1+558 \times 0.1} = 9.8$$

$$R_{of} = \frac{R_o}{1+A\beta} = \frac{1.8}{56.8} = 31.69 k\Omega$$

9.15

Rail-to-Rail OP Amp

All $V_{OV} = 0.2V$ All $V_T = 0.5V$

$V_{DD} = V_{SS} = 1.65V$

$$V_{icm(max)} = V_{DD} - |V_{OV6}| + V_T = 1.65 - 0.2 + 0.5 = +1.95V$$

$$V_{icm(min)} = -V_{SS} + V_{OV11} + V_{OV1} + V_T = -1.65 + 0.2 + 0.2 + 0.5 = -0.75V$$

(a) For NMOS stage

$$-0.75V \leq V_{icm} \leq +1.95V$$

(b) For PMOS stage (symmetrical)

$$-1.95V \leq V_{icm} \leq +0.75V$$

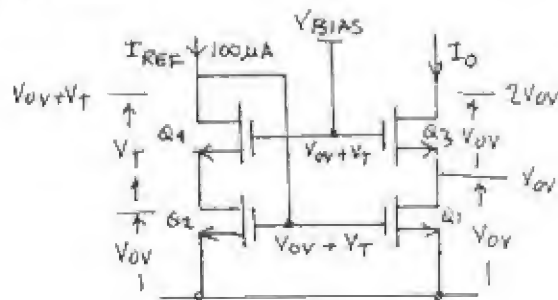
(c) For both active

$$-0.75V \leq V_{icm} \leq +0.75V$$

(d) Overall

$$-1.95V \leq V_{icm} \leq +1.95V$$

9.16



All same $K(W/L) \therefore I_O \approx I_{REF}$

All same $r_o = V_A/I = 10V/100\mu A = 100k\Omega$

$$I = \frac{1}{2} K [W/L] [V_{OV}]^2$$

$V_{D3} = V_O : V_O(min) = 2V_{OV}$

R_O (looking into Q3D and assuming I_O current source is ideal, $r_o' = \infty$)

$$= r_{O3}(1 + g_{m3}r_{O1}) \approx g_{m3}r_{O1}^2$$

$$g_m = \frac{2I}{V_{OV}} = \frac{2 \times 100}{0.2} \Rightarrow 1mA/V$$

$$\text{Then } R_O \approx g_m r_{O1}^2 = 1 \times 10^5 \times 10^5 \approx 10^4 M\Omega$$

9.17

$A = 80dB$ $f_t = 10MHz$ $C_L = 10pF$

$I_B = I$ All same $|V_{OV}|$, $L = 0.5\mu m$
 $|V_A| = 20V$

$$g_m = \frac{2I}{V_{OV}} \quad \text{and} \quad f_t = \frac{g_m}{2\pi C_L}$$

$$A = g_{m1} [g_{m4} r_{O4} (r_{O2} \parallel r_{O6})] \parallel [g_{m6} r_{O6} r_{O2}]$$

$$\text{Consider } Q_1: I_1 = \frac{1}{2} K_n [W/L]_1 [V_{OV}]^2 = \frac{1}{2} 200 [W/L]_1 [V_{OV}]^2$$

$Q_1, Q_2, Q_5, Q_6, Q_7, Q_8$ are same

$$g_{m1} = \frac{2I_1}{V_{OV}} \quad \text{and} \quad r_{O1} = \frac{V_A}{I_1}$$

$$\text{Consider } Q_3, Q_4: I_3 = \frac{1}{2} K_p [W/L]_3 [V_{OV}]^2 \\ I_1 = \frac{1}{2} \frac{200}{2.5} [W/L]_1 [V_{OV}]^2 \\ \Rightarrow [W/L]_3 = 2.5 [W/L]_1$$

$$g_{m3,4} = g_{m1} \quad \text{and} \quad r_{O3,4} = r_{O1}$$

$$\text{Consider } Q_9, Q_{10}: I_{10} = \frac{1}{2} K_p [W/L]_{10} [V_{OV}]^2 \\ 2I_1 = \frac{1}{2} \frac{200}{2.5} [W/L]_{10} [V_{OV}]^2 \\ \Rightarrow [W/L]_{10} = 5 [W/L]_1$$

$$g_{m9,10} = 2g_{m1} \quad \text{and} \quad r_{O9,10} = r_{O1}/2$$

$$\text{Consider } Q_{11}: I_{11} = \frac{1}{2} K_n [W/L]_{11} [V_{OV}]^2 \\ 2I_1 = \frac{1}{2} 200 [W/L]_{11} [V_{OV}]^2 \\ \Rightarrow [W/L]_{11} = 2 [W/L]_1$$

$$g_{m11} = 2g_{m1} \quad \text{and} \quad r_{O11} = r_{O1}/2$$

$$\text{Thus } A = g_{m1} [g_{m4} r_{O1} (r_{O1} \parallel r_{O2})] \parallel [g_{m1} r_{O1} r_{O1}] \\ = g_{m1} [g_{m1} r_{O1} (r_{O1} \parallel \frac{r_{O1}}{2})] \parallel [g_{m1} r_{O1} r_{O1}] \\ 10^4 = \frac{1}{4} g_{m1} g_{m1} r_{O1} r_{O1} \\ \Rightarrow g_{m1} r_{O1} = 200$$

$$\text{Now } g_{m1} r_{O1} = \frac{2I}{V_{OV}} \cdot \frac{V_A}{I}$$

$$\Rightarrow V_{OV} = 2V_A/200 = 2(20)/200 = 0.2V$$

$$\text{Hence } g_{m1} = \frac{1}{2\pi f_t C_L} = 0.628 mA/V$$

$$\rightarrow r_{O1} = 200/g_{m1} = 318k\Omega$$

$$g_m = \frac{2I}{V_{ov}} \Rightarrow I = \frac{g_m V_{ov}}{2}$$

$$\Rightarrow I_1 = \frac{g_{m1} V_{ov}}{2} = \frac{0.628 \text{ mA/V} \times 0.2 \text{ V}}{2}$$

$$= 62.8 \mu\text{A}$$

$$SR = 2\pi f_t V_{ov} = 2\pi \times 10 \times 10^6 \times 0.2 = 12.5 \text{ V}/\mu\text{s}$$

$Q_1, Q_2, Q_5, Q_6, Q_7, Q_8$:

$$I = \frac{1}{2} K_n [W/L] [V_{ov}]^2$$

$$62.8 = \frac{1}{2} \times 200 [W/L] [0.2]^2$$

$$\Rightarrow [W/L]_1 = 15.7$$

For Q_3, Q_4 : $I = \frac{1}{2} \times \frac{200}{2.5} [W/L] [V_{ov}]^2$

$$62.8 = \frac{1}{2} \times \frac{200}{2.5} [W/L] [0.2]^2$$

$$\Rightarrow [W/L]_3 = 2.5 [W/L]_1 = 39.25$$

For Q_9, Q_{10} :

$$[W/L]_9 = 5 [W/L]_1 = 78.5$$

For Q_{11} :

$$[W/L]_{11} = 2 [W/L]_1 = 31.4$$

For $L = 1 \mu\text{m}$: $W_x = [W/L]_x \mu\text{m}$

Width for $Q_1, Q_2, Q_5, Q_6, Q_7, Q_8 = 15.7 \mu\text{m}$

for $Q_3, Q_4 = 39.25 \mu\text{m}$

for $Q_9, Q_{10} = 78.5 \mu\text{m}$

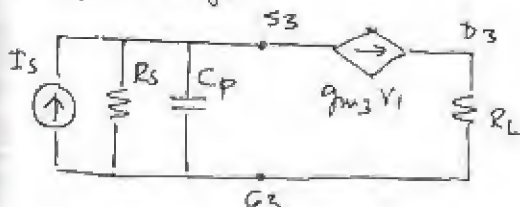
for $Q_{11} = 31.4 \mu\text{m}$

9.18

Simply invert circuit relative to V_{DD}, V_{SS} and reverse all arrows on FETs

9.19

Model for CG stage:



at S_3 : $I_s - g_{m3} V_i - \frac{V_i (1 + s C_p R_s)}{R_s} = 0$

$$\Rightarrow \frac{V_i}{I_s} = \frac{1}{g_{m3} + (1 + s C_p R_s)/R_s}$$

$$= \frac{1}{(g_{m3} + 1/R_s) + s C_p R_s/R_s}$$

3dB down when

$$s C_p = (g_{m3} + 1/R_s)$$

$$\Rightarrow f_{p3} = \frac{(g_{m3} + 1/R_s)}{2\pi C_p} \approx \frac{g_{m3}}{2\pi C_p}$$

Q6D.

Also $f_t \approx \frac{g_{m1}}{2\pi C}$

$$PM = 180 - \phi_{total} = 90^\circ - \tan^{-1} \frac{f_t}{f_2}$$

For $PM = 75^\circ$: $\frac{f_t}{f_2} = \tan 15^\circ = 0.27$

$$\Rightarrow \frac{f_t}{f_2} = \frac{C_p}{C_L} = 0.27$$

$$\Rightarrow C_p = 0.27 C_L$$

20 $V_{BE} = V_T \ln \frac{I_E}{I_S}$

$g_m = \frac{I_E}{V_T}$

$r_e = \frac{V_T}{I_E}$

$r_{\pi} = \beta r_e$

$r_o = \frac{V_A}{I_E}$

$r_{\mu} = \beta \frac{10 V_A}{I_E}$

Device	V_{BE} (mV)	g_m (mA/V)	r_{π} (Ω)	r_e (Ω)	r_o (Ω)	r_{μ} (Ω)
Q1-Q2	517	0.38	2632	564	18.2	26.3
Q3-Q4	520	0.448	1545	309	7.72	15.4
Q5	618	22	455	9.09	0.227	0.45

21 $I_E = I_L \sqrt{\frac{I_{E1} I_{E2}}{I_{E1} I_{E2}}}$
 $= 15.9 \sqrt{\frac{10^{-14} \cdot 10^{-14}}{3 \times 10^{-14} \cdot 6 \times 10^{-14}}}$
 $= \underline{\underline{32.2 \mu A}}$

22 $I_{E101} = 0.73 \text{ mA}$
 $I_{E1} = 0.25(0.73) = 0.1825 \text{ mA}$
 $I_{E2} = 0.75(0.73) = 0.5475 \text{ mA}$
 $V_{BE1} = V_T \ln \frac{0.1825 \times 10^{-3}}{0.25 \times 10^{-14}} = 0.625 \text{ V}$
 $g_{m1} = \frac{I_{E1}}{V_T} = \frac{I_{E2}}{V_T} = 7.3 \text{ mA/V}$
 $r_{\pi 1} = \frac{\beta}{g_{m1}} = \frac{134.3 \Omega}{1}$
 $r_{\pi 2} = (\beta+1) r_{e2} = \frac{6.85 \text{ k}\Omega}{1}$
 $r_{o1} = \frac{V_A}{I_{E1}} = \frac{27.4 \text{ k}\Omega}{1}$
 $V_{CE1} = V_{CE2} = 0.625 \text{ V}$
 $g_{m2} = \frac{0.5475}{25} = 21.9 \text{ mA/V}$
 $r_{e2} = \frac{V_T}{g_{m2}} = \frac{4.5 \Omega}{1}$
 $r_{\pi 2} = (\beta+1) r_{e2} = \frac{2.28 \text{ k}\Omega}{1}$
 $r_{o2} = \frac{91.3 \text{ k}\Omega}{1}$

9

23 Let $V_{BE} = 0$

For breakdown $V_{D1} = V_{BE1} + V_{BE2}$
 $> V_{BE1} + V_{BE2} + 7 + 5.4$

or $V_{D1} \geq \underline{\underline{58.4 \text{ V}}}$

24 $V_{BE1} + V_{BE2} = V_{BE1} + V_{BE2}$

Since V_{BE} 's are equal

$\sqrt{\frac{I_1}{K_1}} + \sqrt{\frac{I_2}{K_2}} = \sqrt{\frac{I_1}{K_1}} + \sqrt{\frac{I_2}{K_2}}$

$\sqrt{I_1} \left[\frac{1}{\sqrt{K_1}} + \frac{1}{\sqrt{K_2}} \right] = \sqrt{I_2} \left[\frac{1}{\sqrt{K_1}} + \frac{1}{\sqrt{K_2}} \right]$

or $\sqrt{\frac{I_1}{I_2}} = \frac{\frac{1}{\sqrt{K_2}} + \frac{1}{\sqrt{K_1}}}{\frac{1}{\sqrt{K_1}} + \frac{1}{\sqrt{K_2}}}$

$K_1 = K_2, K_3 = K_4 = 16 \text{ K}\Omega$

$\sqrt{I_1} = \sqrt{I_2} \sqrt{\frac{K_2}{K_1}}$

or $I_1 = I_2 \frac{K_2}{K_1}$
 $= \frac{I_2}{16} = \underline{\underline{100 \mu A}}$

9

25 $V_{BE} = 0.7$
 $I_{ref} = \frac{5 - 1.4 - 0.5}{R_S}$
 $= \underline{\underline{260.5 \mu A}}$

At this current level
 $V_{BE} = V_T \ln \frac{220.6 \times 10^{-3}}{10^{-14}} = 595 \text{ mV}$

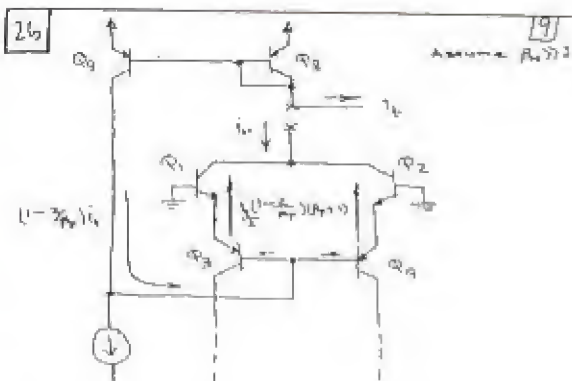
$\Rightarrow I_{ref} = \frac{10 - 2(0.595)}{38 \text{ k}} = \underline{\underline{22.9 \mu A}}$

For $I_{ref} = 0.73 \text{ mA}, V_{BE} = 0.625 \text{ V}$

$R_S = \frac{10 - 2(0.625)}{0.73 \times 10^{-3}} = \underline{\underline{12 \text{ k}\Omega}}$

9

9



29 In this case

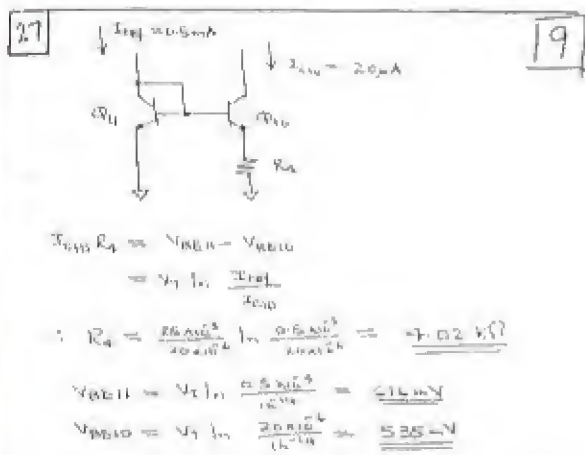
$$\frac{4I}{1 + \beta_P} + \frac{2I}{\beta_P} = I_{C10}$$

For $\beta_P \gg 1$

$$I_{C10} \approx 4I \quad \text{or } I \approx \underline{475 \mu A}$$

To correct we need $I_{C10} = 58 \mu A$

$$\Rightarrow R_4 = \frac{V_T \ln \frac{0.73 \text{ mA}}{I_{C10}}}{I_{C10}} = \underline{1.94 \text{ k}\Omega}$$



30 At $I = 9.5 \mu A$

$$V_{BE5} = V_{BE4} = 517 \text{ mV}$$

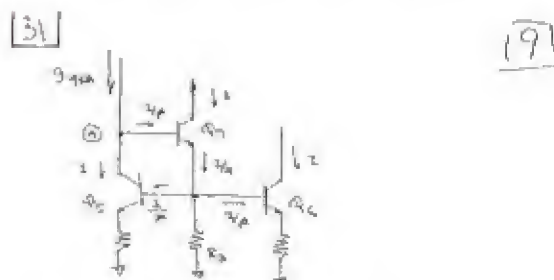
and $V_{BE6} = V_{BE5} + I R_2$

$$= 526.5 \text{ mV}$$

If R_2 is shorted $V_{BE4} = V_{BE6} = 526.5 \text{ mV}$

and $I_{C6} = I_{S6} e^{V_{BE6}/V_T}$

$$= \underline{14 \mu A}$$



$$2I = 9.4 \mu A \quad I = I_P = 4.7 \mu A$$

$$= 1 - \frac{1.4}{1 + \beta_P} = \underline{9.353 \mu A}$$

$$I_{E3} = \frac{I}{\alpha} - \frac{I}{\beta} = 9.307 \mu A$$

$$V_{BE} = I_{E3} R_3 = V_{BE5} + \frac{I_P R_3}{\alpha}$$

$$V_{BE5} = V_T \ln \frac{9.353 \mu A}{10^{-14}} = 516.4 \text{ mV}$$

Thus $V_{BE} = 525.8 \text{ mV}$

and $R_3 = \frac{V_{BE}}{I_{E3}} = \underline{56.5 \text{ k}\Omega}$

28 Assume $\beta_P \gg 1$

$$I_{C10} = \frac{2I}{1 + \beta_P} + \frac{2I}{\beta_P}$$

$$\approx 2I \left(1 - \frac{1}{\beta_P} + \frac{1}{\beta_P} \right)$$

$$= 2I \left(1 - \frac{1}{\beta_P} \right)$$

$$\Rightarrow I \approx \frac{I_{C10}}{2} \left(1 + \frac{1}{\beta_P} \right)$$

Thus $\frac{1}{\beta_P} = 0.1 \Rightarrow \underline{\beta_P = 10}$

Without the above assumption and using the exact relationship $\beta_P = 7.74$

32 Assume equal collector current

$$I_{C1} = I_{C2} = 9.5 \mu A$$

$$I_{OS} = I_{C1} - I_{C2} = \frac{I_{C1}}{\beta_1} - \frac{I_{C2}}{\beta_2}$$

$$= \underline{15.7 \text{ nA}}$$

$$I_P = \frac{1}{2} (I_{C1} + I_{C2})$$

$$= \underline{55 \text{ nA}}$$

33 $I_B = 10 \mu A$, $I_{B2} = 4 \mu A$

Thus, base currents are

$$I_{B1} = (I_B \cdot \frac{2}{3})$$

$$= \frac{20}{3} \mu A$$

$$\beta_{B1} = \frac{95 \mu A}{20/3 \mu A} = 250$$

$$\frac{V_{B1}}{\beta_{B1}} = \frac{4.5 \mu A}{250} = 2.26$$

$$\Rightarrow \Delta P_{B1} = 2 \mu A$$

$$\overline{P_{B1}} = \frac{P_{B1} + \Delta P_{B1}}{2} = 232$$

34 $I_{C1} = I_{C2} = 19 \mu A$

Minor forward $I_{C2} = 0.9 I_{C1}$

$$\text{Thus } I_{C1} = \frac{19}{1.9} \mu A = 10 \mu A$$

$$\text{and } I_{C2} = 9 \mu A$$

$$V_{BE} = 0.7 V_{BE}$$

$$= V_{BE1} - V_{BE2}$$

$$= V_T \ln \frac{10}{9} = 2.63 \text{ mV}$$

35 At $I_{C1} = 550 \mu A$, $V_{BE1} = 618 \text{ mV}$

$$I_{B1} = \frac{550}{200} = 2.75 \mu A$$

$$\Rightarrow I_{C14} = 4.5 \mu A = I_{B1} + \frac{I_{B1} R_2 + V_{BE1}}{R_3}$$

$$\Rightarrow R_3 = 99.7 \text{ k}\Omega$$

36 Neglecting base currents

$$I_{C18} = I_{C19} = \frac{180}{2} = 90 \mu A$$

$$V_{BE18} = V_T \ln \frac{90 \times 10^{-6}}{10^{-14}} = 573 \text{ mV}$$

$$\text{Thus } R_{B1} = \frac{V_{BE18}}{I_{B18}} = 6.37 \text{ k}\Omega$$

$$I_{C14} = 2 \times 10^{-14} e^{\frac{573 \text{ mV}}{26 \text{ mV}}} = 2.70 \mu A = I_{C20}$$

37



$$V_E = V_{BE}$$

If we ignore base currents

$$V_{BE} = \frac{R_1}{R_1 + R_2} V$$

$$\text{and } V = V_{BE} \left(\frac{R_1 + R_2}{R_1} \right)$$

$$V = V_{BE} \left(1 + \frac{R_2}{R_1} \right)$$

38 $I_{V_{CC}} = I_{C12} + I_{C13A} + I_{C13B} + I_{C14} + I_{C19} + I_{C20}$
 $+ I_{C7} + I_{C16}$

$$= (730 + 180 + 550 + 154 + 19 + 19 + 10.5 + 16.2) \mu A$$

$$= 1.68 \text{ mA}$$

$$P_{Diss} = P_{B1} = I_{V_{CC}} (V_{C1} + V_{BE})$$

$$= 1.68 (15 + 15) \text{ mW}$$

$$= 50.4 \text{ mW}$$

39

Series connection of devices requires the same bias currents

$$R_{B1} = (\beta + 1) (4 \text{ k}\Omega)$$

$$I_2 = \frac{V_T}{R_{B1}} = 2.68 \text{ k}\Omega$$

$$R_{B1} = 3.17 \text{ M}\Omega$$

$$I_2 = \frac{V_{BE}}{R_{B1}} ; I_0 = 2.7 \text{ k}\Omega$$

$$\Rightarrow G_{M1} = \frac{I_2}{V_{BE}} = \frac{2}{4 \text{ k}\Omega} = \frac{1}{2 \text{ k}\Omega}$$

$$= 127 \mu A/V$$

$$R_{B4} = R_2 (1 + g_{m1} (R_{B1} || R_1))$$

$$g_{m1} \approx 1/R_2$$

$$R_2 = 2 \text{ k}\Omega + 5.26 \text{ k}\Omega$$

$$R_2 = (\beta + 1) R_1 = 134 \text{ k}\Omega$$

$$\text{Thus } R_{B4} = 15.4 \text{ M}\Omega$$

$$R_{B4} = 18.2 \text{ M}\Omega \text{ (from text)}$$

$$R_{B1} = R_{B4} || R_{B4} = 3.34 \text{ M}\Omega$$

$$G_{M1} R_{B1} = 127 \times 3.34 = 425 \text{ V/V}$$

See gain decreases due to negative feedback.

40

$$R_0 = R_2 (1 + g_{m1} (R_{B1} || R_{B2}))$$

- need to double the second factor

Since $R_{B1} \gg R_2$

$$R_{B2} \approx R_2 (1 + g_{m1} R_2)$$

Thus

$$1 + g_{m1} R_2 = 2 (1 + g_{m1} R_2)$$

$$g_{m1} = \frac{1}{2 \text{ k}\Omega} ; R_2 = 1 \text{ k}\Omega$$

$$\Rightarrow R_0 = 4.63 \text{ k}\Omega$$

44

19

41) $I_{E3} = I_{E4} = I_{E7}$

$\Rightarrow r_{E3} = r_{E4} = r_{E7} = 2.63 \text{ k}\Omega$

(a) $V_{E6} = (r_{E6} + R_E) I_E = 4.63 \text{ k}\Omega \times I_E$

(b) $R_B = 50 \text{ k}\Omega \parallel r_{E5} \parallel r_{E6}$
 $\approx 45.1 \text{ k}\Omega$

$\Rightarrow I_{E7} = \frac{V_{E6}}{R_B} = 0.103 I_E$

(c) $I_{E7} = \frac{I_{E7}}{\beta+1} = \frac{0.103}{201} I_E = 0.51 \mu\text{A} \times I_E$

(d) $V_{E7} = V_{E6} + r_{E7} I_{E7}$
 $= (4.63 \text{ k}\Omega + 2.63 \text{ k}\Omega \times 0.103) I_E$
 $= 4.9 \text{ k}\Omega \times I_E$

(e) $R_{in} = \frac{V_{E7}}{I_E} = 4.9 \text{ k}\Omega$

42) From eqn 9.85

$\frac{\Delta I}{I} = \frac{\Delta R}{R + \Delta R + r_E}$

$\Delta I \approx \text{Gain } V_{os} = \frac{V_{os}}{2 r_E}$

Thus $\frac{V_{os}}{2 r_E I} = \frac{\Delta R}{R + \Delta R + r_E} ; r_E I = V_T$

$\frac{V_{os}}{2 V_T} = \frac{\Delta R}{R} \left[\frac{1}{1 + \frac{r_E}{R} + \frac{\Delta R}{R}} \right] (*)$

$\frac{V_{os}}{2 V_T} (1 + \frac{r_E}{R}) = \frac{\Delta R}{R} (1 - \frac{V_{os}}{2 V_T})$

$\frac{\Delta R}{R} = \frac{V_{os}}{2 V_T} \frac{1 + \frac{r_E}{R}}{1 - \frac{V_{os}}{2 V_T}}$

(b) $V_{os} = 5 \text{ mV}, r_E = 2.63 \text{ k}\Omega, R = 1 \text{ k}\Omega$

$\frac{\Delta R}{R} = \frac{5}{2(25)} \frac{1 + 2.63}{1 - \frac{5}{50}} = 0.40$

(c) R_2 completely shorted

$\Rightarrow \frac{\Delta R}{R} = -1$

From (*) $\frac{V_{os}}{2 V_T} = -1 \frac{1}{r_E/R}$

$\Rightarrow V_{os} = -19 \text{ mV} \quad (\text{or } 19 \text{ mV})$

43) Current in the collector of Q_3 remains unchanged at $9.5 \mu\text{A}$

Thus $I_{E3} = I_{E4} = \frac{9.5}{20} 9.5 \mu\text{A} = 9.69 \mu\text{A}$

$I_{E4} = \frac{35}{26} I_{E4} = 3.317 \mu\text{A}$

$\Rightarrow \Delta I = 9.5 - 3.317 = 0.183 \mu\text{A}$

$V_{os} = \frac{\Delta I}{\text{Gain}} = 2 r_E \Delta I = 2(2.63 \text{ k}\Omega)(0.183 \mu\text{A})$
 $= 0.96 \text{ mV}$

45) Working with Common-mode half circuits

$I_{E3} = \frac{\beta_F}{\beta_F + 1} \frac{V_{icm}}{r_{E1} + r_{E2} + \frac{2R_E}{\beta_F + 1}}$

$= \frac{\beta_F V_{icm}}{(\beta_F + 1)(r_{E1} + r_{E2}) + 2R_E}$

Similarly

$I_{E4} = \frac{\beta_F V_{icm}}{(\beta_F + 1)(r_{E1} + r_{E2}) + 2R_E}$

46) Recall that for a resistor degenerated mirror the current gain is given, approximately, by

$\frac{I_2}{I_1} \approx \frac{R_{E1}}{R_{E2}}$ where R_E is the total emitter resistance.

(a) R_1 shorted

$\frac{I_2}{I_1} = \frac{r_{E1}}{r_{E2} + R_2} = \frac{2.63}{2.63 + 1} = 0.72$

Thus $I_2 = (0.72) I_1$ (cf 2.1e)

Since the output impedance is unaffected, the gain is thus reduced by 14% ($\frac{1.32-1}{1}$)

(b) R_2 shorted

$\frac{I_2}{I_1} = \frac{r_{E1} + R_1}{r_{E2}} = \frac{2.63}{2.63} = 1.32$

$\Rightarrow I_2 = (1.32) I_1 = 2.38 \mu\text{A}$

Note that the output of the mirror decreases because of the lack of degeneration from R_2 . Neglecting this, since R_{E1} is largely determined by R_{E2} , gain increases by $\frac{2.32-2}{2} = 16\%$.

(c) Current gain remains at unity. Thus $I_2 = I_1$ and gain is unaffected.

47) Since β_n is typically very large we will ignore its effect

$R_1 = \frac{125}{9.5 \mu\text{A}} = 13.16 \text{ k}\Omega$

$R_3 = \frac{5}{9.5 \mu\text{A}} = 5.26 \text{ k}\Omega$

$R_E = (\beta_F + 1) \left[r_{E1} + \left(r_{E2} + \frac{2R_E}{\beta_F + 1} \right) \parallel r_{E1} \parallel r_{E3} \right]$
 $= 201 \left[2.63 \text{ k}\Omega + \left(2.63 \text{ k}\Omega + \frac{4.5 \text{ k}\Omega}{51} \right) \parallel 13.16 \text{ k}\Omega \parallel 5.26 \text{ k}\Omega \right]$
 $= 19.5 \text{ k}\Omega$

Since $R_E = 2 R_{Em}$

$R_{Emf} = \frac{R_E}{2} (1 + \beta_F)$ See problem #8
 $= 497 \text{ M}\Omega$

48 $R_{12} = (\beta + 1) [r_{e16} + R_{17} \parallel R_3]$

$r_{e16} = 1.54 k\Omega$

$r_{e17} = 45 \Omega$

$R_{17} = 20(45.5 - 50) = 19.4 k\Omega$

$\Rightarrow R_{12} = 20(1.54 + 19.4 \parallel 150) k\Omega = \underline{3.14 k\Omega}$

$$V_{b17} = \frac{R_{12} \parallel R_3}{r_{e16} + R_{12} \parallel R_3} V_{12}$$

$= 0.9 V_{12}$

$$I_{b17} = \frac{V_{b17}}{r_{e17} + R_3} = 0.74 \mu A$$

$\Rightarrow I_{c17} = \frac{8(0.7)}{45.5 + 50} = \underline{9.88 \mu A/V}$

49 $R_{b17} = 787 k\Omega$

$I_{c18} = 550 \mu A$

$I_{c18} = 22 \mu A/V ; r_{e18} = 100(1/550) = 232 \Omega$

$r_o = \frac{50}{550 \mu A} = 90.9 \Omega$

$$R_{b18} = r_o \left(1 + \beta_m (R_E \parallel R_A) \right)$$

 $= 90.9 [1 + 22(R_E \parallel 352)]$
 $= 787$

$\Rightarrow R_E \parallel 352 = 4.34 k\Omega$

and $\frac{1}{R_E} = 2.14$ or $R_E = 0.465 k\Omega$

$R_E = 410 \Omega$

Current $\frac{R_{E12}}{R_E} = \frac{550 \mu A}{730 \mu A} \Rightarrow R_{E12} = \underline{307 \Omega}$

$\frac{R_{E13A}}{R_E} = \frac{550}{180} = \underline{1.25 k\Omega}$

50 $V_o = V_{cc} - V_{ce(sat)15} - V_{BE14}$
 $= \underline{7.2 V}$

$$V_o = -V_{CE} + V_{ce(sat)15} + V_{BE23} + V_{BE20}$$

 $= -5 + 0.2 + 0.6 + 0.4$
 $= \underline{-3.8 V}$

9

51 With Q_{12} removed, current in Q_{11} increases to $730 \mu A$. This changes G_{m2}

$r_{e17} = \frac{V_T}{I_{b17}} = 34.2 \Omega$

$\Rightarrow G_{m2} = 0.323 \frac{A}{V} = 4.3 \text{ mA/V}$

Because $r_{e17} \gg r_{e18}$, R_{E2} remains virtually unchanged at $81 k\Omega$

$R_{B3} = (\beta + 1) R_{E2} \parallel r_{e18A} = 74 k\Omega$

$\Rightarrow A_2 = -4.3(81) \frac{74}{74 + 81} = \underline{-26.4 V/V}$

52 Ignore base currents of Q_{18}
 $I_{c18A} = I_{c18} + \frac{1}{\beta + 1} I$, where $I = I_{c18}$

$I_{c18} = I_{c18} + \frac{I}{\beta + 1}$, where $V_{BE} = 0.7 V$

Thus $I = \frac{V_{12}}{2.7} \ln \left[\frac{180 \mu A - \frac{1}{2.7}}{I_{c18}} \right]$

$= 191.422 \mu A$

$\approx 195.2 \mu A$

output current is limited to $520 \mu A$ (see problems 35 and 36)

$\Rightarrow |V_{CE}| < 20 \text{ mV (10)}$

$|V_o| < 4 V$

To obtain a fixed solution, let $I = 0$

on RHS $\Rightarrow I = \frac{V_{12}}{2.7} \ln \frac{180 \mu A}{12.7} = 21.9 \mu A$

iterating $I = 21.0 \mu A$

53 Maximum output current of the 1st stage = $19 \mu A$

$\Rightarrow I_{c22} = 19 \mu A \Rightarrow V_{BE22} = V_{BE24} = 534 \text{ mV}$

$\Rightarrow I_{R11} = \frac{534}{50} = 10.7 \mu A$

$\therefore I_{c21} = (19 + 10.7) \mu A = 29.7 \mu A$

and $V_{BE21} = 545.3 \text{ mV}$

$V_{BE21} = I R_7 \Rightarrow I = \underline{20.2 \mu A}$

A simple doubling of R_7

54 $\frac{V_o}{V_i} = \frac{2+3.147}{0.97} = 250.667 \text{ V/V} \approx \underline{10\% \text{ dB}}$

$\frac{R_o}{R_o + R_L} = 0.2 \Rightarrow R_o = R_L \left(\frac{1}{0.2} - 1 \right)$

or $R_o = 619 \Omega$

$\left. \frac{V_o}{V_i} \right|_{f=0} = 250.667 \frac{200}{200 + 61.9}$

9.58 dominant pole $f_p = \frac{1}{2\pi R(A C_c)}$; $A = 1000$

with single pole response

$A_{f_p} = f_c \Rightarrow f_p = \frac{5 \times 10^6}{10^4} = 5 \text{ Hz}$

$\Rightarrow R = \frac{1}{2\pi(5)(1000)(20 \mu\text{F})} = \underline{637 \text{ k}\Omega}$

55 Bode PM says that 2nd pole introduces 18° of phase shift at unity

i.e. $\tan^{-1} \frac{f_c}{f_{p2}} = 18^\circ$

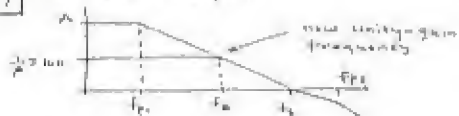
or $f_{p2} = \underline{5.07 \text{ kHz}}$

56 Each pole adds 90° of phase shift

$\tan^{-1} \frac{10}{f_{2,3}} = 90^\circ$

$\Rightarrow f_{2,3} = \underline{11.4 \text{ MHz}}$

57 Consider Bode plot



80° of closed-loop phase margin

$\tan^{-1} \frac{10}{f_{p2}} = 90^\circ$

or $f_{p2} = \underline{437 \text{ kHz}}$

Recalling the 'bandwidth' effect of negative feedback, we get

$f_{p2} = f_{p1}(1 + A\beta) = f_{p1} A\beta$

Loop gain $A\beta = 2.43 \times 10^6 \frac{1}{100} = 2.43 \times 10^4$

$\Rightarrow f_{p1} = \underline{180 \text{ Hz}}$

$f_{p2} = \frac{G_{m1}}{2\pi C_c} = 437 \text{ kHz}$

$\Rightarrow C_c = \frac{1}{5.26 \times 10^4 (2\pi) (437 \times 10^3)}$

$= \underline{0.69 \text{ pF}}$

9.59

DC gain is

$A_{DC} = G_{m1} R_c$
 $= (10 \mu\text{A/V}) \times 10^4$
 $= 10^5 \text{ V/V}$

$f_p = \frac{1}{2\pi R_c C_c} = \frac{1}{2\pi (10^4) (20 \times 10^{-9})}$

$= 31.8 \text{ Hz}$

$f_c = A_{DC} f_p$
 $= 31.8 \text{ kHz}$



$SR = \frac{2I}{C_c}$

$G_{m1} = \frac{I}{2V_T} \Rightarrow 2I = 4G_{m1}V_T$

$SR = \frac{4G_{m1}V_T}{C_c} = \frac{4(10 \mu\text{A/V})(25 \times 10^{-9})}{50 \times 10^{-12}}$
 $= \underline{20 \text{ V}/\mu\text{s}}$

9.60 $SR = 10 \text{ V}/\mu\text{s}$

$|V_{max}| = 10 \text{ V}$

For sine wave of amplitude V_{max} , maximum rate of change

$\left. \frac{dv}{dt} \right|_{max} = \omega_{in} \hat{V}_0 = 2\pi f_m \hat{V}_0$

Thus $2\pi f_m \hat{V}_0 = SR$

$= f_m = \frac{10 \times 10^6}{2\pi (10)} = \underline{159.2 \text{ kHz}}$

$f_c = \frac{SR}{2\pi(V_T)} = \frac{10 \times 10^6}{2\pi (4) (25 \times 10^{-9})}$

$= \underline{159 \text{ kHz}}$

Chapter 10 - Problems

1 Ideal 3V logic implies:

$$V_{OH} = V_{DD} = 3.0V, V_{OL} = 0.0V;$$

$$V_{IH} = V_{DD}/2 = 3.0/2 = 1.5V;$$

$$V_{IL} = V_{DD}/2 = 1.5V; V_{TH} = V_{DD}/2 = 1.5V$$

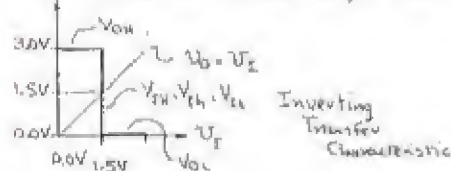
$$NM_H = V_{OH} - V_{IH} = 3.0 - 1.5 = 1.5V$$

$$NM_L = V_{IL} - V_{OL} = 1.5 - 0.0 = 1.5V$$

The gain in the transition region is:

$$(V_{OH} - V_{OL}) / (V_{IH} - V_{IL}) =$$

$$= (3.0 - 0.0) / (1.5 - 1.5) = 3/0 = \infty V/V$$



2 Nearly ideal 3.3V logic, assumed ideal:

$$\rightarrow V_{OH} = 3.3V, V_{OL} = 0.0V, V_{IH} = 0.7(3.3) = 2.31V$$

Now, at V_{IH} , $v_O = v_I$, so to reach $v_O = 1.32V$

the required input is $1.32 / (-50) = -26.4 \mu V$

$$\text{Thus, } V_{IL} = 1.32 - 26.4 \times 10^{-3} = 1.294V$$

$$\text{Likewise, } V_{TH} = 1.32 + (3.3 - 1.32)/50 = 1.360V$$

Best possible noise margins are:

$$NM_H = V_{OH} - V_{TH} = 3.30 - 1.360 = 1.940V$$

$$NM_L = V_{TH} - V_{OL} = 1.360 - 0.0 = 1.360V$$

For noise margins only 7/10 of these, and

V_{OH} , V_{OL} still ideal:

$$V_{IH} = 3.3 - 0.7(1.940) = 1.942V, \text{ and}$$

$$V_{IL} = 0.0 + 0.7(1.360) = 0.952V$$

Correspondingly, the large-signal voltage gain is:

$$G = (3.3 - 0.0) / (0.952 - 1.942) = -3.18 V/V$$

Here, $V_{OH} = 1.2V$, and $V_{OL} = 0.0V$.

$$\text{Also, } V_{OH} - V_{OL} \leq 1.2/3 = 0.4V \quad \text{--- (1)}$$

Now, the noise margins are "within 20% of one other". Thus $NM_H = (1 \pm 0.3) NM_L$ or

$$NM_L = (1 \pm 0.3) NM_H. \text{ Thus to remain "within"}$$

$$\text{either } NM_H = 1.3 NM_L, \text{ or } NM_L = 1.3 NM_H,$$

$$\text{in which case, either } NM_L = 0.769 NM_H, \text{ or}$$

$$NM_H = 0.769 NM_L$$

$$\text{For the former case: } 0.769(V_{OH} - V_{TH}) = (V_{IL} - V_{OL})$$

$$\text{or } 0.769(1.2 - V_{TH}) = V_{IL} - 0, \text{ whence}$$

$$V_{IL} = 0.923 - 0.769 V_{TH}$$

$$\text{Now, from (1), } V_{TH} = V_{IL} + 0.4.$$

$$\text{Thus, } V_{IL} = 0.923 - 0.769(V_{IL} + 0.4) = 0.615 - 0.769 V_{IL}$$

$$\text{and } V_{IL} = 0.615 / 1.769 = 0.349V,$$

$$\text{whence } V_{TH} = 0.4 + 0.349 = 0.749V. \quad \text{10}$$

Alternatively, $NM_H = 0.769 NM_L$, and

$$(V_{OH} - V_{TH}) = 0.769(V_{IL} - V_{OL}), \text{ or}$$

$$1.2 - V_{TH} = 0.769 V_{IL} - 0, \text{ and } V_{TH} = 1.2 - 0.769 V_{IL}$$

$$\text{With (1), } V_{IL} + 0.4 = 1.2 - 0.769 V_{IL}, \text{ and}$$

$$1.769 V_{IL} = 0.8, \text{ whence } V_{IL} = 0.452V$$

$$\text{and } V_{TH} = 0.4 + 0.452 = 0.852V$$

$$\text{Thus, overall, } V_{OH} = 1.2V, V_{OL} = 0.0V,$$

$$V_{TH} \text{ ranges from } 0.749V \text{ to } 0.852V, \text{ and}$$

$$V_{IL} \text{ ranges from } 0.349V \text{ to } 0.452V, \text{ in}$$

which case, margins can be as low as:

$$NM_L = V_{IL} - V_{OL} = 0.349V, \text{ and}$$

$$NM_H = V_{OH} - V_{TH} = 1.2 - 0.852 = 0.348V,$$

$$\text{and as high as } 0.452V, \text{ and } 0.451V.$$

4

a) Generally, $t_p = (t_{PHL} + t_{PLH})/2$,but due to current ratio, $t_{PHL} = 0.5 t_{PLH}$.Thus $1.5 t_{PLH} = 2(1.2 \text{ ns})$, whence

$$t_{PLH} = 2.4/1.5 = 1.6 \text{ ns, and } t_{PHL} = 0.8 \text{ ns}$$

$$\text{Check: } t_p = (1.6 + 0.8)/2 = 1.2 \text{ ns}$$

b) Generally, $t_p = CV/\bar{I} = kC$

$$\text{Originally, } 1.2 = kC \quad \text{--- (1)}$$

$$\text{Then, } 1.7(1.2) = k(C+1) \quad \text{--- (2)}$$

$$\text{Dividing (2)/(1): } 1.7 = (C+1)/C$$

$$\text{Thus, } 1.7C = C+1, 0.7C = 1, C = 1.43 \text{ pF}$$

(the combined load and output capacitance)

c) With the load inverter removed:

$$0.6(1.2) = k(1.43 - C_{in}) \quad \text{--- (3)}$$

$$\text{Dividing (3)/(1): } 0.6 = (1.43 - C_{in})/1.43$$

$$\text{Thus, } C_{in} = 1.43(1 - 0.6) = 0.57 \text{ pF; } C_{out} = 1.43 - 0.57 = 0.86 \text{ pF}$$

10

7

a) For current proportional to V_{DD} ,reduction in current (and frequency) is to $2.3/5 = 0.46$ or 46% of previous (or by 54%)b) For current proportional to V_{DD}^2 ,reduction is to $(2.3/5)^2 = 0.436$ or 44% of previous (or by 56%).For case a), delay increases by $1/0.46 = 1.515$

times, and power reduces (from Eq 13.4) to

$$0.46 \times (2.3/5)^2 = 0.287 \text{ of previous, for}$$

a net change in DP to $1.515 \times 0.287 =$

$$0.435 \text{ of previous, a net decrease by } 56.5\%$$

For case b), delay increases by $1/0.436 = 2.29$ times, and power reduces to $0.436(2.3/5)^2 =$

$$0.190 \text{ of previous, for a net change in DP to } 2.29 \times 0.190 = 0.435 \text{ of previous (by } 56.5\%)$$

5

Average static current (at 50% duty cycle)

$$\text{is } (0 + 40)/2 = 20 \mu\text{A}$$

When switching at 100 MHz, current is 150 μA Dynamic current is $(150 - 20) = 130 \mu\text{A}$, and

$$\text{dynamic power is } P_D = (3.3 \text{ V})(130 \mu\text{A}) = 429 \mu\text{W}$$

$$\text{But, } P_D = fCV_{DD}^2, \text{ and } C = 429 \times 10^{-6} / (100 \times 10^6 \times 3.3)$$

$$\text{Thus } C_{eq} = C = 0.394 \text{ pF}$$

10

8

a) For current proportional to $(V_{DD} - V_T)$ i) For $V_T = 1 \text{ V}$: Change in current to

$$(3.3 - 1)/(5.0 - 1) = 0.575, \text{ or } 57.5\% \text{ of previous,}$$

a decrease of 42.5%

Change in delay to $1/0.575 = 1.74$ or

an increase of 74%.

Change in frequency to 0.575 or 57.5% of previous.

Change in dynamic power due to change

in both voltage and frequency is to

$$0.575 \times (3.3/5)^2 = 0.250 \text{ or } 25\% \text{ of previous.}$$

Change in DP is to $1.74 \times 0.25 = 0.435$, or

$$43.5\% \text{ of previous, a decrease of } 56.5\%$$

ii) For $V_T = 0.5 \text{ V}$:

$$\text{Current: to } (3.3 - 0.5)/(5.0 - 0.5) = 0.622, \text{ to } 62.2\% \text{ (net)}$$

6

Now, $P_D = fCV_{DD}^2$. Thus for V_{DD} reducedfrom 5V to 3.3V, power reduces by a factor $(3.3/5)^2 =$

$$0.436. \text{ For frequency reduced by a factor } (2.3/5),$$

$$\text{additional power saved is } ((5 - 3.3)/5) \times 10^{-3} \times 0.436 =$$

$$1.48 \text{ mW.}$$

Check: First reduction is to $10(0.436) = 4.36 \text{ mW}$, and

$$\text{the second to } 4.36(2.3/5) = 2.02 \text{ mW, by } 4.36 - 2.02 = 2.34 \text{ mW}$$

[8]

Delay: to $1/0.622 = 1.61$, to 161%Frequency: to 62.2%Dynamic Power: to $0.622 (3.3/5.0)^2 = 0.271$, to 27.1%Delay-Power (DP): to $1.61 \times 0.271 = 0.436$, to 43.6%(iii) For $V_t = 0V$ (as in P10.7)Current: to $3.3/5.0 = 0.66$, to 66%Delay: to $1/0.66 = 1.515$, to 151.5%Frequency: to $1/1.515 = 0.66$, to 66%Dynamic Power: to $0.66 (3.3/5.0)^2 = 0.281$, to 28.1%Delay-Power (DP): to $1.515 \times 0.281 = 0.435$, to 43.5%b) For current proportional to $(V_{DD} - V_t)^2$ i) For $V_t = 1V$:Current: to $[(3.3-1)/(5.0-1)]^2 = 0.331$, to 33.1%Delay: to $1/0.331 = 3.02$, to 302%
(next)

[8]

Frequency: to $1/3.02 = 0.331$, to 33.1%Dynamic Power: to $0.331 (3.3/5.0)^2 = 0.144$, to 14.4%Delay-Power (DP): to $3.02 \times 0.144 = 0.435$, to 43.5%(ii) For $V_t = 0.5V$:Current: to $[(3.3-0.5)/(5.0-0.5)]^2 = 0.387$, to 38.7%Delay: to $1/0.387 = 2.58$, to 258%Frequency: to $1/2.58 = 0.387$, to 38.7%Dynamic Power: to $0.387 (3.3/5.0)^2 = 0.163$, to 16.3%Delay-Power (DP): to $2.58 \times 0.163 = 0.435$, to 43.5%(iii) For $V_t = 0V$ (as in P10.7):Current: to $[3.3/5.0]^2 = 0.436$, to 43.6%Delay: to $1/0.436 = 2.30$, to 230%Frequency: to $1/2.30 = 0.436$, to 43.6%Dynamic Power: to $0.436 (3.3/5.0)^2 = 0.190$, to 19.0%Delay-Power (DP): to $2.30 \times 0.190 = 0.437$, to 43.7%

[10]

[9]

Chip area changes to $0.9 \times 0.9 = 0.81$ of prevCurrent changes only due to oxide change, since
changes cancel, to $1/0.9 = 1.11$ of previousEffective Capacitance: half changes by 0.9^2 to 0.81
half changes by $0.9^2/0.9 = 0.9$ Net Capacitance changes by $(0.81 + 0.90)/2 = 0.855$ Propagation Delay changes by $(1/1.11)0.855 = 0.770$ Max. Operating Frequency changes by $1/0.770 = 1.30$ Dyn. Power Diss. (at max. freq) changes by $1.30 \times 0.855 = 1.11$ Delay-Power Product changes by $0.770 \times 1.11 = 0.855$ Performance (C/A) changes by $1.30/0.81 = 1.60$

Now, if the supply voltage is reduced by 10%

(but V_t is not, remaining at $0.2V_{DD}$), $(V_{DD} - V_t)$ changes to $(0.9V_{DD} - 0.2V_{DD}) = 0.7V_{DD}$
or to $(0.7V_{DD}/0.8V_{DD}) = 0.875$ of previous

[9]

[10]

Thus, current changes by $(1/0.4)(0.875)^2 = 0.875$

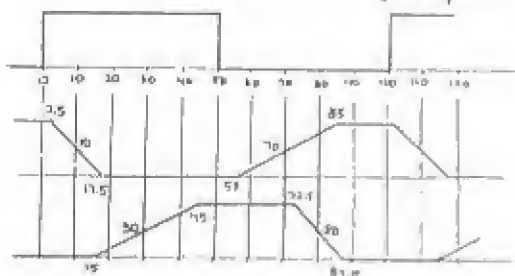
Assume capacitances are voltage-independent.

Thus, propagation delay changes by $(1/0.875)0.855 = 1.005$ Maximum frequency changes by $1/1.005 = 0.995$ Dyn. Power changes by $(0.995)(0.855)(0.9)^2 = 0.689$ Delay-Power product changes by $1.005(0.689) = 0.693$ Performance (C/A) changes by $0.995/0.81 = 1.23$

10

The results depend on whether the gates are inverting or non-inverting.

For inverting gates, the timing diagram is:



Note: For simplicity, 0% to 100% (rather than 10% to 90%) both in the diagram above and calculation to follow:

For inverting gates (as shown above):

- For a rising input, time to 90% change of output of second gate is $10 + 20 + 30/2 = 45\text{ns}$
- For a falling input, time to 90% change

10

of output of 2nd gate is $20 + 10 + 15/2 = 37.5\text{ns}$

For non-inverting gates:

- Time to 90% rise is $10 + 10 + 15/2 = 27.5\text{ns}$
- Time to 90% fall is $20 + 20 + 30/2 = 55\text{ns}$

The propagation delay for these gates is

$$t_p = (t_{pHL} + t_{pLH})/2 = (10 + 20)/2 = 15\text{ns}$$

11

Note that this question ignores the possibility of dynamic power dissipation:

Average propagation delay is $t_p = (50 + 70)/2 = 60\text{ns}$

Average power loss at 50% duty cycle $= (1 + 0.5)/2 = 0.75\text{mW}$

Delay-Power product is $DP = 60 \times 10^{-9} \times 0.75 \times 10^{-3}$

$$\approx DP = 45 \times 10^{-12} \text{ J} = 45\text{pJ}$$

10

10.12

10.13

14

For $V_E = 1.5\text{V}$, the NMOS operates in triode mode, while the PMOS is cut off.

$$V_{DSN} = [k_n(V_E - V_{th})]^{-1} = [100 \times 10^{-6} (1.5 - 0.5)]^{-1} = 10\text{mV}$$

$$\text{Thus } V_{DS} = 100 \times 10^{-6} \times 10^{-9} / (10^{-6} \times 10^{-9}) = 9.09\text{mV}$$

For $V_E = -1.5\text{V}$, the PMOS operates with

$$V_{DSp} = [k_p(V_E - V_{th})]^{-1} = [100 \times 10^{-6} (1.5 - 0.5)]^{-1} = 10.5\text{mV}$$

$$\text{Thus } V_{DS} = 100 \times 10^{-6} \times 10^{-9} / (10^{-6} \times 10^{-9}) = 50\text{mV}$$

10

15

At V_{th} , both transistors operate in

saturation with $V_{th} = V_E = V_D = V$,

$$\text{at which } I_D = \frac{k_n}{2} (V - V_{th})^2 = \frac{k_p}{2} (V_{DD} - V - V_{th})^2$$

$$\text{Thus } V_{DD} - V - |V_{thp}| = \sqrt{k_n/k_p} (V - V_{thn})$$

$$V (1 + (k_n/k_p)^{1/2}) = V_{DD} - |V_{thp}| + V_{thn} (k_n/k_p)^{1/2}$$

$$\text{Thus } V = V_{th} = \frac{V_{DD} - |V_{thp}| + V_{thn} (k_n/k_p)^{1/2}}{1 + (k_n/k_p)^{1/2}}$$

as presented in Equation 10.8

10

10.16

10.17

10.18

19

NMOS width is $3\mu\text{m}$; PMOS width is $2(25) = 50\mu\text{m}$

Total output capacitance $= (20 + 8) \times 30 = 108\text{fF}$

$$\text{Now, } t_p = 1.5C / [k'(W/L) V_{DD}]$$

$$\text{Thus } t_p = 1.6(106)10^{-15} / [75 \times 10^4 (2/0.8) 3.3] = 68.5\text{ps}$$

10

20 From Eq. 10.14, 10.15, 10.16:

10

$$C_{DNLV} = \frac{1}{2} \left[\frac{1}{2} k_n' (W/L)_n (V_{DD}(1-\alpha))^2 + k_n' (W/L)_n (V_{DD}(1-\alpha)) V_{DD}/2 - \frac{1}{2} (V_{DD}/2)^3 \right]$$

$$= \frac{1}{2} k_n' (W/L)_n \left[V_{DD}^3 (1-\alpha)^2/2 + V_{DD}^3 (1-\alpha)/2 - V_{DD}^3/8 \right]$$

$$= \frac{1}{8} k_n' (W/L)_n V_{DD}^3 [(1-\alpha)^2 + (1-\alpha) - 1/4]$$

Now, see the term [] becomes:

$$[1 - 2\alpha + \alpha^2 + 1 - \alpha - 1/4] = \alpha^2 - 3\alpha + 1.75$$

$$\text{Thus, } t_{PHL} = (C V_{DD}/2) / C_{DNLV} = \frac{4C/2}{k_n' (W/L)_n V_{DD} (\alpha^2 - 3\alpha + 1.75)}$$

$$\text{or } t_{PHL} = \frac{2C}{k_n' (W/L)_n V_{DD} (\alpha^2 - 3\alpha + 1.75)}$$

Check: for $\alpha = 0.2$, $(\alpha^2 - 3\alpha + 1.75) = 0.2^2 - 3(0.2) + 1.75 = 1.15$
and the multiplier in the numerator is $\frac{2}{1.15} = 1.74 \approx 1.7$

20

10

For $\alpha = 0.1$, $\alpha^2 - 3\alpha + 1.75 = 0.1^2 - 3(0.1) + 1.75 = 1.46$

and the multiplier becomes $2/1.46 = 1.37$

For $\alpha = 0.5$, $\alpha^2 - 3\alpha + 1.75 = 0.5^2 - 3(0.5) + 1.75 = 0.25$

and the multiplier becomes $2/0.25 = 8.0$

10.21

22

10

Dynamic Power is $P_D = f C V_{DD}^2$; Static Power is P_S .

$$\text{Now, } 9.0 = P_S + 120 \times 10^6 C \cdot 5^2$$

$$\text{and } 4.7 = P_S + 50 \times 10^6 C \cdot 5^2$$

$$\text{Subtracting, } 4.3 = 70 \times 10^6 C (25)$$

$$\text{Whence } C = 4.3 / (25 \times 70 \times 10^6) = 2.457 \text{ pF}$$

$$\text{and } P_S = 9.0 - 120 \times 10^6 (2.457 \times 10^{-12}) \times 5^2 = 9.0 - 7.37 = 1.63 \text{ W}$$

For 70% of the gates active, total gates = 0.7×10^4

$$\text{Capacitance per gate is } 2.457 \times 10^{-12} / (0.7 \times 10^4) = 3.51 \text{ fF}$$

10.23

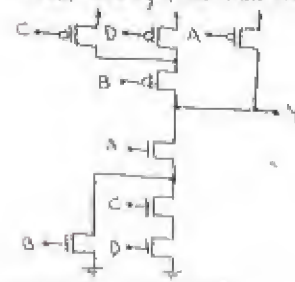
10.24

25

10

For $Y = \overline{A + B(C+D)}$, the PDN can be

drawn directly, and then the PUN as direct dual:



26

10

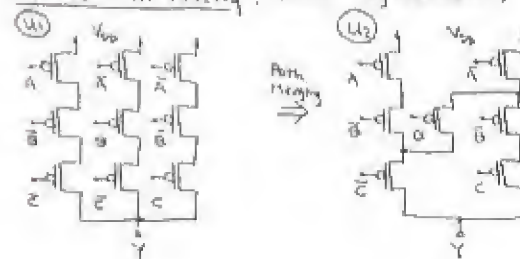
$$Y = \overline{A}BC + A\overline{B}C + AB\overline{C}$$

Any direct implementation would need:

$2(3 \times 3) = 18$ MOS for the gate itself, plus

$3 \times 2 = 6$ for the required inverters, for a total of 24 transistors.

For the PUN directly: (Inverting variables)



For the PUN, $Y = \overline{A}BC + A\overline{B}C + AB\overline{C}$.

$$\text{Correspondingly: } \overline{Y} = \overline{\overline{A}BC + A\overline{B}C + AB\overline{C}} = \overline{\overline{A}BC} \cdot \overline{A\overline{B}C} \cdot \overline{AB\overline{C}} = (A+B+\overline{C})(\overline{A}+\overline{B}+\overline{C})(\overline{A}+\overline{B}+C) \text{ --- (1)}$$

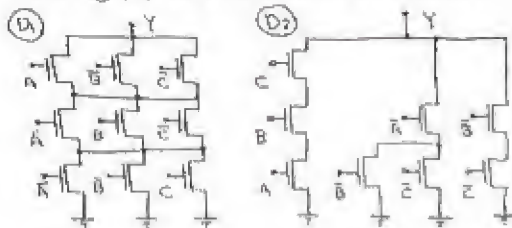
$$\overline{Y} = ABC + \overline{A}\overline{B}C + A\overline{B}\overline{C} + \overline{A}B\overline{C} + \overline{A}B\overline{C} + \overline{A}B\overline{C} \text{ --- (2)}$$

(next)

26

For the PDN directly:

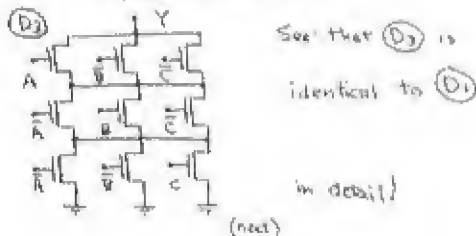
From (1), $\bar{Y} = (A + \bar{B} + \bar{C})(\bar{A} + B + \bar{C})(\bar{A} + \bar{B} + C)$



From (2), $\bar{Y} = ABC + \bar{A}\bar{B} + \bar{A}\bar{C} + \bar{B}\bar{C}$, see (D2) where path merging is included

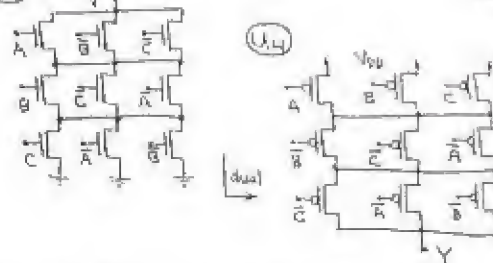
For the PDN from the PUN (U1)

Simply, replacing series connections with parallel connections:



See that (D2) is identical to (D1) in detail (next)

(D4) (recovered (D1))

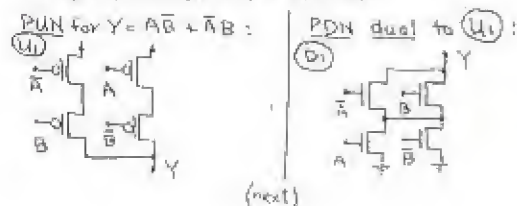


See that (U4), while not the same as (U1), is highly related, having some variable exchange in the middle and right columns. Clearly, there are lots of variations of the completely-connected array.

27

$$Y = AB + \bar{A}\bar{B} \rightarrow \bar{Y} = \overline{AB + \bar{A}\bar{B}} = \bar{A}\bar{B} + \bar{A}\bar{B}$$

$$\text{or } \bar{Y} = (\bar{A} + B)(A + \bar{B}) = AB + \bar{A}\bar{B}$$

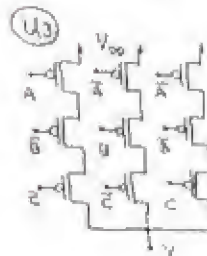


27

For the PUN from the PDN (D1)

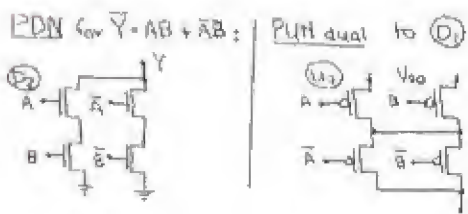
See that both parallel and series connections can be identified for transformation, but that the series (vertical) ones (as drawn) contain variables and their complements, and are therefore always open.

Thus converting parallel paths to series ones



See this is the same as (U1)

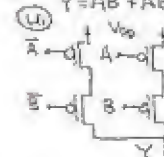
Note, however that (D1) can be redrawn as shown, then its columns (series links) converted to rows (parallel links of a PUN):



The two circuits required are (U1) with (D1) and (U3) with (D2)

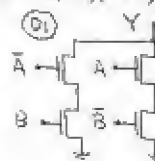
28

$Y = AB + \bar{A}\bar{B}$. Directly, the PUN is as follows:



$$\text{Now, } \bar{Y} = \overline{AB + \bar{A}\bar{B}} = \bar{A}\bar{B} + \bar{A}\bar{B} = (\bar{A} + \bar{B})(A + B)$$

Directly, the PDN is:



29

$Y = ABC + \bar{A}\bar{B}\bar{C}$. Directly, the PUN is shown below:

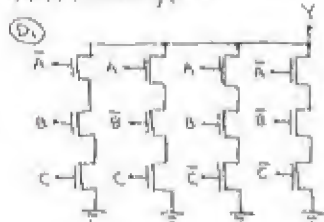


The corresponding dual PUN is shown above right.

30

Even-parity circuit: $\bar{Y} = \bar{A}\bar{B}C + \bar{A}B\bar{C} + A\bar{B}\bar{C} + ABC$

PUN, directly, is:



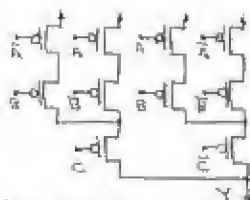
It uses 12 transistors

31

For output high with odd parity:

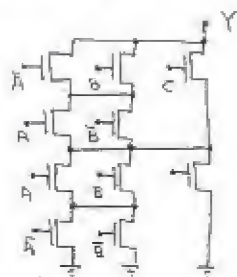
$$Y = \bar{A}\bar{B}\bar{C} + \bar{A}B\bar{C} + \bar{A}BC + A\bar{B}\bar{C} + A\bar{B}C + ABC = (\bar{A}\bar{B} + \bar{A}B)C + (\bar{A}B + AB)C$$

Directly the PUN is:



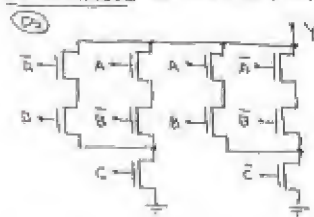
[Note that two transistors could be eliminated by combining the B and A inputs in a non-planar topology.]

Using duality, the PUN becomes:

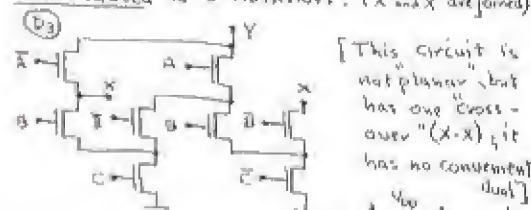


31

PUN reduced to 10 transistors:



PUN reduced to 8 transistors: (X and X are joined)

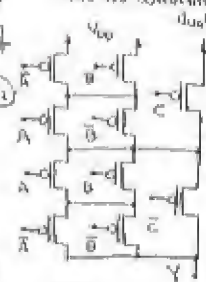


[This circuit is not planar, but has one 'cross-over' (X-X); it has no convenient dual.]

PUN as the dual of D2:

[Think of the structure of the dual of (D1) when constructing this.]

The complete circuit, using (U1) and (D2) has 20 transistors



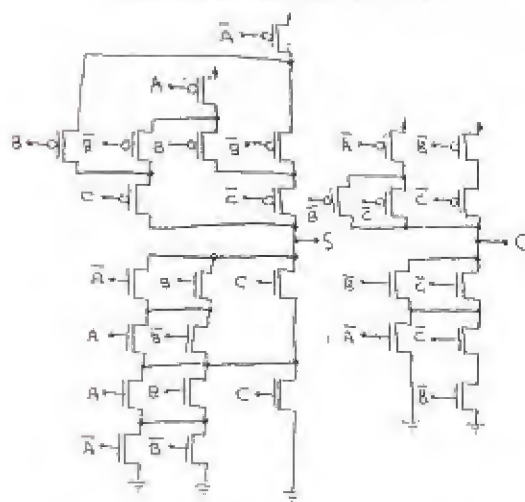
32

$$\text{Sum } S = \bar{A}\bar{B}\bar{C} + \bar{A}B\bar{C} + \bar{A}BC + ABC$$

$$\begin{aligned} \text{Carry } C_0 &= \bar{A}\bar{B}\bar{C} + \bar{A}B\bar{C} + \bar{A}BC + ABC \\ &= \bar{A}B + \bar{A}C + BC = A(B+C) + BC \end{aligned}$$

Create the PUNs directly, simplifying that for S as in PIC20 above, as

$$S = \bar{A}(B\bar{C} + \bar{B}C) + A(\bar{B}\bar{C} + BC)$$



33 For matched-inverter equivalence of the

circuit in Fig 13.14: $R_A = R_P = R_B = R_C = R_D = 2P$
and $n_A = n_B = 2n$; $n_C = n_D = 2(2n) = 4n$.

10.34

35 Ignore the capacitances of the transistors

themselves. For the matched NMOS, $t_{PLH} = t_{PHL} = t_P$.

For the "uncompensated" NMOS, $t_{PLH} = t_P$, $t_{PHL} = t_P/4$.

Thus t_{PLH} are the same, but t_{PHL} is 4 times greater with no matching.

36 For design a), there are $2(6) + 2 = 14$ transistors.

All 7 NMOS use $(W/L)_n = n$

1 PMOS uses $(W/L)_p = p$

6 PMOS use $(W/L)_p = 6p$

Total Area = $7(1.2)0.8 + 1(3.6)0.8 + 6(6)(3.6)0.8 = 113.3 \mu m^2$

For design b), there are $2(3)2 + 1(2)2 = 16$ transistors:

6 NMOS use $(W/L)_n = n$

6 PMOS use $(W/L)_p = 3p$

2 PMOS use $(W/L)_p = p$

2 NMOS use $(W/L)_n = 2n$

Total equivalent devices is $6n + 18p + 2p + 2n = 10n + 20p$

Total equivalent area is $[10 + 3(20)]n = 70n$, and

Total Area = $70(1.2)0.8 = 67.2 \mu m^2$, or 59% of a)

37 Corresponding to a matched inverter characterized by n and p where $k_p = k_n/k$, the two-input NOR uses transistors n and $2p$ when $k_p = 2k_n$.

a) For A grounded, V_{th} occurs near $V_{DD}/2$, with Q_{n1} and Q_{n2} in saturation and Q_{p1} in triode. Let $V_{th} = V$, and the voltage across Q_{n1} be x .

Thus $i_D = k_p[(5-x) - x]^2/2$

and $i_D = \frac{1}{2}k_p(5-x-V)^2$

and $i_D = \frac{1}{2}k_n(15-x)^2$

For $k_p = 2k_n$, $i_D = 2k_n(4x - x^2/2) = k_n(8x - x^2) \dots (1)$

and $i_D = k_n(4-x-V)^2 \dots (2)$

and $i_D = \frac{1}{2}k_n(15-x)^2 \dots (3)$

From 2) 3): $(15-x)(0.101) = 4-x-V$

Thus, $1.707V = 4.707 - x$ or $x = 4.707 - 1.707V$

Now $x \approx 0$, in which case, $V_{th} = 4.707/1.707 = 2.78(0V)$
or $V_{th} = 7.203/0.293 = 24.6V$ (Clearly too large)

Thus $x = 4.707 - 1.707V \dots (4)$

Now, from 1) 3): $(15-x)^2 = 2(8x - x^2)$

With 4), $15^2 - 2Vx + 1 = 16(4.707 - 1.707V)^2 - 2(4.707 - 1.707V)^2$

or $15^2 - 2Vx + 1 = 75.32 - 27.32V - 44.31 + 72.13V - 5.83V^2$

or $6.83V^2 + Vx(2+27.32-72.13) + (1-75.32+44.31) = 0$

or $6.83V^2 - 6.81V - 30.01 = 0$

whence $V_{th} = (-(-6.81) \pm \sqrt{(-6.81)^2 - 4(6.83)(-30.01)})/2(6.83)$

$= (6.81 \pm 29.43)/13.66 = 2.65V$

Check: $[> 2.5V$ probably OK since one PMOS is full on]

Thus $V_{th} = 2.65V$

b) For A and B joined, the PMOS can be approximated as a single device with twice the length, for which the width is twice that in a matched inverter. Thus, for the equivalent PMOS device, $(W/L)_{p1} = p$ and $k_p = k$. For each of the two NMOS, $(W/L)_n = n$ and $k_n = k$.

Thus at $V_{th} = V$ with all devices in saturation:

tion:

(next)

$$i_D = 2k/2 (v-1)^2 = k/2 (5-v-1)^2, \quad [10]$$

$$2(v-1)^2 = (4-v)^2, \text{ and } \pm\sqrt{2}(v-1) = (4-v)$$

Thus, $1.414v - 1.414 = 4 - v$, $2.414v = 5.414$,
whence $V_{th} = v = \underline{2.24V}$

See this is reduced from the single-input value (of 2.65V)!

Note that this fact can be used to control the relative threshold of multiple gates connected to a single fanout node - in order to guarantee operation sequence for slowly changing signals.

[38] For the resistor load, the output voltage rising is $V_D = V_{DD}(1 - e^{-t/(R_D C)})$.
This reaches $V_{DD}/2$ when $(1 - e^{-t/(R_D C)}) = 0.5$,
or $e^{-t/(R_D C)} = 0.5$, and $t = -R_D C \ln 0.5 = 0.693 R_D C$.
Thus $t_{PH} = 0.693 R_D C$.
For the current load, $I = V_D/R_D$, the output reaches $V_{DD}/2$ when $t = (C V_{DD}/2)/I$,
or $t = (C V_{DD}/2)/(V_{DD}/R_D) = 0.5 R_D C$ (next)

[10] Now, $k_n = k_n' (W/L)_n = 75 \times 10^{-6} (1.2/0.8) = 112.5 \mu A/V^2$
and $k_p = 0.256 \times 112.5 = 28.8 \mu A/V^2$

Now, $k_p' (W/L)_p = 28.8$; Thus $(W/L)_p = 28.8 / (154 \times 10^{-6}) = 187$

For $L_p = 0.8 \mu m$, $W_p = 1.152 (0.8) = 0.923 \mu m$

In summary, for this inverter: $k_n = 112.5 \mu A/V^2$
 $k_p = 28.8 \mu A/V^2$
and $V = k_n/k_p = 3.91$

Now, $V_{OH} = +5.0V$

For $V_{OL} = v \approx 0$, $i_D = k_p/2 (V_{GS} - V_t)^2$
or $i_D = (28.8/2) (5.0 - 0.8)^2 = 25 \mu A$

For the NMOS, $25 \mu A = 112.5 [(5 - 0.8)v - v^2/2]$
or $v^2 - 8.4v + 4.52 = 0$

whence $v = (-(-8.4) \pm (8.4^2 - 4(1)(4.52))^{1/2})/2$
 $= (8.40 \pm 7.24)/2 = 0.58V$

Thus $V_{OL} = 0.58V$

[10] Thus $t_{PH} = 0.5 R_D C$ - a reduction to
(0.50/0.69) $\times 100 = 72.5\%$ or by $\frac{0.50 - 0.58}{0.58} \times 100 = 21.8\%$

[39] Here $V_{DD}/4 = 5/4 = 1.25V$

Now, for V_D rising, the NMOS is cutoff, and the PMOS is in triode mode with:

$i_D = k_p [(V_{GS} - V_t) V_{SD} - V_{SD}^2/2]$, and here
 $i_D = k_p [(5 - 0.8)(5 - 1.25) - (5 - 1.25)^2/2]$
 $= k_p (15.15 - 7.02) = 8.12 k_p$

Now, for V_D falling, the net current extracted from the load is $i_{DN} - i_{DP}$ which should be i_{DP}

Thus $i_{DN} = 2 i_{DP} = 2(8.12) k_p$, for triode operation where $i_{DN} = k_n [(5 - 0.8)(1.25 - 1.25)^2/2]$

Overall, $i_{DN} = 2(8.12) k_p = k_n (5.25 - 0.78) = 11.47 k_n$
Thus $k_n = (11.47 / (2(8.12))) k_p = 0.256 k_n$

Check using Eq 10.34, where $V = k_n/k_p = 3.91$:
 $V_{OH} = (V_{DD} - V_t) [1 - (1 - V)^{1/2}]$
 $= (5 - 0.8) [1 - (1 - 1/3.91)^{1/2}] = 0.57V$

From Eq 12.95, $V_{OL} = V_t + (V_{DD} - V_t) / (1 + V)^{1/2}$
 $= 0.8 + 4.2 / (3.91 + 4.91)^{1/2} = 1.16V$

From Eq 12.38, $V_{th} = V_t + (2/\sqrt{V}) (V_{DD} - V_t)$
 $= 0.8 + (2/\sqrt{3.91}) 4.2 = 3.25V$

From Eq 12.36, $V_M = V_t + (V_{DD} - V_t) / (1 + V)^{1/2}$
 $= 0.8 + 4.2 / (4.91)^{1/2} = 2.70V$

Now, $NM_{H} = V_{OH} - V_{th} = 5.00 - 3.25 = 1.75V$

and $NM_L = V_{OL} - V_{OL} = 1.74 - 0.58 = 1.18V$

40

Note that a design with $r=2$ sacrifices V_{OL} for improved propagation-delay symmetry.

$$\text{From Eq. 10.39, } V_{OL} = (V_{DD} - V_t) \left[1 - (1 - V_{OL})^{1/2} \right] \\ = (5 - 0.8) \left[1 - (1 - V_{OL})^{1/2} \right] = 1.23V$$

$$\text{Now, } k_n'(W/L)_n = 75(1.2/0.8) = r k_p = 2(75/3)(W/L)_p \\ \text{Thus, } (W/L)_p = (70/25) \times 1/2 = (1.2/0.8) = (1.8/0.8)$$

$$\text{Now } C_{gsn} = 1.2(1.5) = 1.8 \text{ fF}; C_{gsn} + 1.2(0.5) = 0.4 \text{ fF} \\ \text{Thus } C_{in} = 1.8 + 0.4 = 2.4 \text{ fF.}$$

Now, the output capacitance includes C_{db} and C_d of the load plus C_{db} and twice C_{gs} of the load.

Thus, the total capacitance of the output and the loading gate is:

$$C_{out} = 1.2(0.5 + 2) + 1.2(2.0 + 2(0.5)) + 2.4 = 10.5 \text{ fF}$$

$$\text{Now, from Eq. 10.43, } t_{PLH} = 1.75 / (k_p V_{DD}) \\ \text{and } t_{PLH} = 1.75 \times 10.5 \times 10^{-15} / (75/3) \times 10^4 (1.2/0.8) = 1.75 \text{ ps}$$

$$\text{Now, from Eq. 10.44, } t_{PHL} = 1.75 / [k_n (1 - 0.46)^{1/2}] \\ \text{and } t_{PHL} = 1.75 \times 10.5 \times 10^{-15} / (75/3) \times 10^4 (1.2/0.8) \times (1 - 0.46)^{1/2} = 4.12 \text{ ps}$$

$$\text{Thus } t_p = (t_{PHL} + t_{PLH})/2 = (4.12 + 1.75)/2 = 2.94 \text{ ps}$$

$$\text{Thus } (2v+1)(v-1) = (v+1)^2 \\ \text{and } (4v^2 + 4v + 1)(v-1) = (v^2 + 2v + 1)(v+1) \\ 4v^3 + 4v^2 + v - 4v^2 - 4v - 1 = v^3 + 2v^2 + v + v^2 + 1 \\ 4v^3 - 3v - 1 = v^3 + 3v^2 + 2v + 1 \\ 3v^3 - 3v^2 - 6v - 2 = 0 \\ v^3 - v^2 - 2v - 2/3 = 0$$

$$\text{Test } v^3 - v^2 - 2v - 2/3 \\ v=2 \rightarrow 8 - 4 - 4 - 2/3 = -2/3 \\ v=3 \rightarrow 27 - 9 - 6 - 2/3 = 11/3 \\ v=2.1 \rightarrow 2.1^3 - 2.1^2 - 4.2 - 2/3 = 9.26 - 4.41 - 4.2 - 0.67 = 0.04$$

$$\text{Thus } v \approx 2.1, \text{ for which:} \\ NM_L = 0.8 - (5.0 - 0.8) \left[1 - (1 - 1/2.1)^{1/2} - (2.1(2.1+1))^{-1/2} \right] \\ = 0.8 - 4.2 \left[1 - 0.724 - 0.352 \right] = 1.29V$$

41

$$\text{From Eq. 10.41, } NM_L = V_t - (V_{DD} - V_t) \left[1 - (1 - \frac{1}{2})^{1/2} - (r(v+1))^{1/2} \right]$$

$$\text{Now, } \frac{\partial NM_L}{\partial v} = -(V_{DD} - V_t) \left[-\frac{1}{2} (1 - \frac{1}{2})^{-1/2} - \frac{1}{2} (r(v+1))^{-1/2} \right]$$

$$\text{Maximum occurs where:} \\ = \frac{1}{2} (1 - \frac{1}{2})^{-1/2} = \frac{1}{2} (r(v+1))^{-1/2} (2v+1)$$

$$\text{Square both sides: } (1 - \frac{1}{2})^{-1/2} = r^{-1/2} (v+1)^{-1/2} (2v+1) \\ \text{or } 1 - \frac{1}{2} = \frac{r}{(v+1)^2} (2v+1)^2 = \frac{r}{v-1}$$

43

$$\text{From Eq. 10.41, } NM_H = (V_{DD} - V_t) \left(1 - \frac{2}{\sqrt{3v}} \right)$$

$$\text{This is zero when } 1 - \frac{2}{\sqrt{3v}} = 0, \\ \text{or } \sqrt{3v} = 2, \text{ or } 3v = 4, \text{ or } v = \frac{4}{3}$$

$$\text{For } v=1, NM_H = 4.2 \left(1 - \frac{2}{\sqrt{3}} \right) = 0.15V$$

$$\text{For } v=2, NM_H = 4.2 \left(1 - \frac{2}{\sqrt{6}} \right) = 0.72V$$

$$\text{For } v=4, NM_H = 4.2 \left(1 - \frac{2}{\sqrt{12}} \right) = 1.78V$$

$$\text{For } v=8, NM_H = 4.2 \left(1 - \frac{2}{\sqrt{24}} \right) = 2.48V$$

$$\text{For } v=16, NM_H = 4.2 \left(1 - \frac{2}{\sqrt{48}} \right) = 2.92V$$

But, what about NM_L ? (For $v=16$, it is 0.72V)

44

From Eq. 10.41 and 10.42, noise margins are equal when

$$V_t - (V_{DD} - V_t) \left[1 - (1 - \frac{1}{2})^{1/2} - \frac{1}{\sqrt{3v}} \right] = (V_{DD} - V_t) \left[1 - \frac{2}{\sqrt{3v}} \right] \\ \text{or } V_t / (V_{DD} - V_t) = 2 - \frac{2}{\sqrt{3v}} - (1 - \frac{1}{2})^{1/2} - \frac{1}{\sqrt{3v}} = 1 - \frac{1}{\sqrt{3v}}$$

$$\text{Here } V_t / (V_{DD} - V_t) = 0.8 / (5.0 - 0.8) = 0.1905$$

Try various values of v to solve (1):

$$\text{For } v=2, f(v) = 2 - 2/\sqrt{6} - (1 - 1/2)^{1/2} - 1/\sqrt{6} \\ = 2 - 0.82 - 0.707 - 0.408 = 0.069$$

$$\text{For } v=3, f(v) = 2 - 2/\sqrt{9} - (1 - 1/3)^{1/2} - 1/\sqrt{9} \\ = 2 - 0.667 - 0.816 - 0.333 = 0.184$$

$$\text{Try } v=2.8, f(v) = 2 - 2/\sqrt{7.8} - (1 - 1/2.8)^{1/2} - 1/\sqrt{7.8} \\ = 2 - 0.690 - 0.802 - 0.307 = 0.199$$

$$\text{Try } v=2.7, f(v) = 2 - 2/\sqrt{7.3} - (1 - 1/2.7)^{1/2} - 1/\sqrt{7.3} \\ = 2 - 0.703 - 0.793 - 0.316 = 0.188$$

Conclude $v \approx 2.72$, for which the margins are:

$$NM = NM_H = NM_L = (V_{DD} - V_t) \left(1 - \frac{2}{\sqrt{3v}} \right)^{1/2} \\ = 4.2 \left(1 - \frac{2}{\sqrt{3(2.72)}} \right)^{1/2} = 1.26V$$

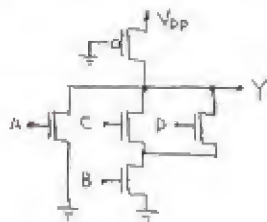
10.45

10.42

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$$Y = A + B(C+D), \text{ whence } \bar{Y} = \bar{A} + \bar{B}(\bar{C} + \bar{D})$$

Thus the PDN can be formed directly as shown:



$$\text{Now, } t_{\text{PH}}/t_{\text{PL}} = (k_n/k_p)(1 - 0.45/v) \\ = v(1 - 0.45/v) = 2.72 - 0.45 = 2.27$$

$$\text{Now, } t_{\text{PH}} = 1.7(1 + 10^{-12}) / (25 \times 10^4 (1.3 V_{DD} - 0.8)) = 8.24 \text{ ns}$$

$$\text{and } t_{\text{PL}} = 8.24 / 2.27 = 3.63 \text{ ns}$$

$$\text{and } t_p = (8.24 + 3.63) / 2 = 5.94 \text{ ns}$$

Now, dynamic power is approximately $f C V_{DD}$, since the output swing is not quite V_{DD} .

For equal static and dynamic power

$$F = 10^{-12} \times 5^2 = 1.82 \times 10^{-11}$$

$$\text{whence } F = 1.82 \times 10^{-11} / (25 \times 10^4) = 72.8 \text{ MHz}$$

$$\text{for which the period is } 1/(72.8 \times 10^6) = 13.7 \text{ ns}$$

Now, for transition times in the same proportion as propagation delays $t_{\text{PH}}/t_{\text{PL}} = 2.27$

Now, for full output swing, there must be time for 2 full transitions in each cycle:

$$\text{Thus } t_{\text{PH}} \approx 13.7 / (1 + 2.27) = 4.59 \text{ ns, and}$$

$$t_{\text{PL}} \approx 4.59 / 2.27 = 2.02 \text{ ns}$$

Since these values are of the same order as the propagation delays, full swing operation is likely not possible at 72.8 MHz.

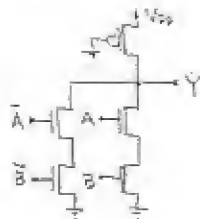
47

For an Exclusive OR, $Y = A\bar{B} + \bar{A}B$, and

$$\bar{Y} = \overline{A\bar{B} + \bar{A}B} = \bar{A}\bar{B} \cdot \bar{\bar{A}B} = (\bar{A} + B)(A + \bar{B})$$

$$\text{or } \bar{Y} = \bar{A}\bar{B} + AB$$

The PDN results directly:



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For a pseudo-NMOS NOR gate, independent of the number of inputs, the worst-case value of V_{OL} occurs for one input high (and as if NMOS conducting)

$$\text{From Eq. 10.34, } V_{OL} = (V_{DD} - V_t) [1 - (1 - V_r)^{1/2}]$$

$$\text{for which } 0.2 = (5.0 - 0.8) [1 - (1 - V_r)^{1/2}]$$

$$\text{and } (1 - V_r)^{1/2} = 1 - 0.2/4.2 = 0.952$$

$$\text{Thus } 1 - V_r = 0.907$$

$$V_r = 0.093, \text{ and } v = 10.76$$

$$\text{Thus } k_n/k_p = 10.76 = 75(1.8/1.2) / (25(V_{DD}/V_t)^2)$$

$$\text{Thus } (W/L)_p = (75/25)(1.8/1.2)/10.76 = 0.418$$

$$\text{Thus for } W_n = 1.8 \mu\text{m}, L_p = 1.8/0.418 = 4.31 \mu\text{m}$$

$$\text{and } (W/L)_p = (1.8/4.31)$$

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For a), see directly that $X = 1, \bar{A} = \bar{A}$

$$\text{and } Y = X \cdot \bar{B} = \bar{A} \cdot \bar{B}$$

For b), see directly that $Y = \bar{A} \cdot \bar{B}$

For each circuit, node Y nominally satisfies both conditions. However in a), with A high and B low, Y is not pulled down completely to ground,

but remains at V_{OL} , due to the PMOS threshold. Circuit b) does not have this problem, but node X is floating for A, B both high. However, X is

not an output node. The body effect makes this worse. Notice that b) is exactly a complementary CMOS

NOR gate for which $Y = \bar{A} \cdot \bar{B} = \overline{A+B}$

For V_{DD} replaced by an inverter driven by C, $Y = \bar{C}(\bar{A} \cdot \bar{B}) = \bar{A} \cdot \bar{B} \cdot \bar{C} = \overline{A+B+C}$, a 3-input NOR (for both a) and b).

Practically speaking, however, there is a problem because, as noted above, the series PMOS do

not operate well with a low input. In fact Y is pulled down only to one threshold drop below ground, when C is high.

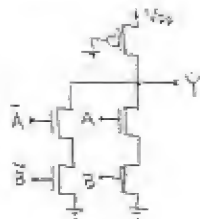
10

For an Exclusive OR, $Y = A\bar{B} + \bar{A}B$, and

$$\bar{Y} = \overline{A\bar{B} + \bar{A}B} = \bar{A}\bar{B} \cdot \bar{\bar{A}B} = (\bar{A} + B)(A + \bar{B})$$

$$\text{or } \bar{Y} = \bar{A}\bar{B} + AB$$

The PDN results directly:



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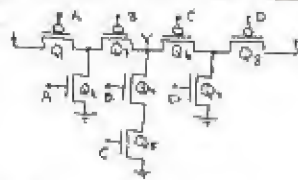
With these reversals, the output is high when B is low or when A is low.

Thus, $Y = \bar{A} + \bar{B}$, or $\bar{Y} = \bar{A} \cdot \bar{B}$, a NAND function

Circuit b), being a fully complementary CMOS gate, functions ideally. However circuit b) provides a

relatively low high output for A low with B high. In this case, the output becomes $V_{DD} - V_{th}$, where V_{th} is raised from V_{thn} by the body effect.

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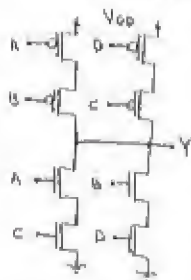


There are several deficiencies:

First, there are two possibilities for short circuits when B and C are low and A and D are complementary, in which case current flows (for example) through Q_1, Q_3, Q_6, Q_7 . This problem occurs for $\bar{A}BCD$ and $AB\bar{C}\bar{D}$.

Second, node Y is pulled down to V_t (increased by the body effect) when B or C are low with A or D high, respectively. In this respect, this circuit is like that in Fig P13.49a.

With respect to Y as a function of A, B, C, D, the result will depend on device sizing. For Q_3, Q_7 , relatively weaker than the PMOS, $Y = \bar{A}\bar{B} + \bar{C}\bar{D}$. A better circuit is shown below:



For Q_3, Q_6 relatively weaker, $Y = A + D + BC$ and $Y = \bar{A} + \bar{D} + \bar{B}\bar{C} = \bar{A}\bar{B}(\bar{C} + \bar{D}) = \bar{A}\bar{B}\bar{C} + \bar{A}\bar{B}\bar{D}$

With input E driving an inverter to replace both V_{DD} connections, $Y = \bar{E}(\bar{A}\bar{B} + \bar{C}\bar{D})$ is possible, having all the other problems this circuit brings.

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For the switch gate and the input both at 3.3 V, the switch output is

$$V_{OH} = 3.3 - V_t \text{ where } V_t = V_{t0} + \gamma(\sqrt{V_{OH}} - \sqrt{V_{t0}})$$

$$\begin{aligned} \text{Thus } V_{OH} &= 3.3 - 0.8 - 0.5(V_{OH} + 0.6)^{1/2} + 0.5(0.6)^{1/2} \\ &= 2.5 - 0.5(V_{OH} + 0.6)^{1/2} \\ \text{or } 2V_{OH} - 5.77 &= (V_{OH} + 0.6)^{1/2} \end{aligned}$$

$$\begin{aligned} \text{Squaring, } V_{OH} + 0.6 &= 4V_{OH}^2 - 23.1V_{OH} + 32.21 \\ 4V_{OH}^2 - 24.1V_{OH} + 31.61 &= 0 \text{ and} \end{aligned}$$

$$\begin{aligned} V_{OH} &= (-24.1 \pm \sqrt{24.1^2 - 4(4)(31.61)})/8 \\ \text{or } V_{OH} &= (24.1 \pm 8.59)/8 = 1.94V \text{ (and a large one)} \end{aligned}$$

Now, for input low and switch gate high, $V_{OL} = 0V$

For the inverter current: For $V_{OH} = 1.94V$, the

PMOS is in saturation with

$$i_D = \frac{1}{2} \mu_p C_{ox} (W/L)_p (3.3 - 1.94 - 0.8)^2 = \frac{1}{2} (75(10^{-4})/3(8.3)) (0.56)^2$$

Thus, the static inverter current is $17.64 \mu A$

For t_{PLH} : Here, $V_D = 0$, $V_t = 1/2 V_{t0} = 0.8V$, $V_{DS} = V_{DD} = 3.3V$

Thus, initially, $i_{D0} = \frac{1}{2} (75)(1.2/0.8)(3.3 - 0.8)^2 = 351.6 \mu A$

$$\begin{aligned} \text{At } V_D &= 3.3/2 = 1.65V, \\ V_t &= 0.8 + 0.5(1.65 + 0.6)^{1/2} - 0.5(0.6)^{1/2} = 1.16V \end{aligned}$$

$$\text{and } i_{D1} = \frac{1}{2} (75)(1.2/0.8)(3.3 - 1.16 - 0.8)^2 = 115.5 \mu A$$

$$\text{Thus } i_{D_{av}} = (351.6 + 115.5)/2 = 183.6 \mu A$$

$$\text{and } t_{PLH} = (C V_{DD}/2) / i_{D_{av}} = 100(10^{-15}) 1.65 / (183.6 \times 10^{-6}) = 0.907 ns$$

For t_{PHL} : Here, $V_t = V_{t0}$ and the initial current is

$$i_{D0} = \frac{1}{2} (75)(1.2/0.8)(3.3 - 0.8)^2 = 352 \mu A$$

At half swing, operation is in triode mode, and

$$i_D(t_p) = 75(1.2/0.8) [(3.3 - 0.8) 1.65 - 1.65^2/2] = 311 \mu A$$

Thus, the average current is $(352 + 311)/2 = 332 \mu A$

$$\text{and } t_{PHL} = 100(10^{-15}) 1.65 / 332 \times 10^{-6} = 0.503 ns$$

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a) For the inverter, with $V_{O2} = 3.3 - 0.8 = 2.5V$, Q_n is in saturation and the current is

$$i_{O1} = \frac{1}{2}(75)(1.2/0.8)(V_{DD} - 0.8)^2 = 56.25(V_{DD} - 0.8)^2$$

and Q_p is in triode mode with current

$$i_{O1} = \frac{1}{2}(75)(3.4/0.8)\left[(3.3 - V_{O1} - 0.8)0.8 - 0.8^2/2\right]$$

$$\text{or } i_{O1} = 100[(2.5 - V_{O1})(0.8 - 0.8^2/2) - 40(2.5 - V_{O1}) - 32]$$

$$\text{Now } i_{O1} = i_{O2} \text{, or } 56.25(V_{DD} - 0.8)^2 = 80(2.5 - V_{O1}) - 32$$

$$\text{Thus, } V_{O1}^2 - 1.6V_{DD} + 0.64 + 2.56 = 1.422V_{DD} - 0.568$$

$$\text{or } V_{O1}^2 - 0.178V_{DD} - 2.35 = 0$$

$$\text{whence } V_{O1} = \frac{-(-0.178) \pm \sqrt{(-0.178)^2 - 4(-2.35)}}{2} = \frac{0.178 \pm 3.07}{2} = \frac{1.62V}{2}$$

$$\text{For } Q_1, V_1 = 0.8 + 0.5[(1.62 - 0.8)^2 - 0.64] = 1.158V$$

Capacitor charging current:

$$\text{At } V_{DD}: i_{C1} = \frac{1}{2}(75)(1.2/0.8)(3.3 - 1.158)^2 = 15.3 \mu A$$

$$\text{At } 0V: i_{C1} = \frac{1}{2}(75)(1.2/0.8)(3.3 - 0.8)^2 = 351.6 \mu A$$

$$\text{Average } i_{C1} = (15.3 + 351.6)/2 = 183 \mu A$$

$$\text{Now, } t_{PLH} = 20 \times 10^{-15} \times 1.62 / 183 \times 10^{-6} = 177.93$$

b)

$$\text{For the inverter, } V_{TH} = \frac{1}{2}(5(3.3) - 2(0.8)) = 1.8V$$

$$\text{For this value, } i_{O1} = 75(1.2/0.8)[(3.3 - 0.8)1.8 - 1.8^2/2] = 324 \mu A$$

$$\text{Current in } Q_n = (75/3)(W/L)_n(3.3 - 0.8)^2 = 378/2$$

$$\text{for which } (W/L)_n = 1.05, \text{ and for } L_n = 0.8 \mu m, (W/L)_n = (0.84/0.8)$$

For t_{PHL} : For Q_1 with source grounded and gate at V_{DD} while Q_n has a source-to-gate voltage V_{GS} .

$$\text{Initially, at } V_{O1} = V_{DD}, i_{O1} = 0, \text{ since } V_{GS} = 0V,$$

$$\text{and } i_{O1} = \frac{1}{2}(75)(1.2/0.8)(3.3 - 0.8)^2 = 351.6 \mu A$$

$$\text{At } V_{O1} = V_{TH}, i_{O1} = 25(0.8/0.80)[(3.3 - 0.8)(3.3 - 1.8) - (3.3 - 1.8)^2/2] = 67.3 \mu A$$

$$\text{and } i_{O1} = 75(1.2/0.8)[(3.3 - 0.8)1.6 - 1.6^2/2] = 328 \mu A$$

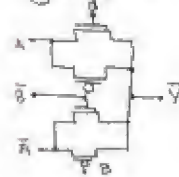
$$\text{where average current for capacitor charging is}$$

$$i_{O1} = (352 + 328 - 67.3)/2 = 306 \mu A$$

$$\text{Thus, } t_{PHL} = 20 \times 10^{-15}(3.3 - 1.86)/(306 \times 10^{-6}) = 99.01$$

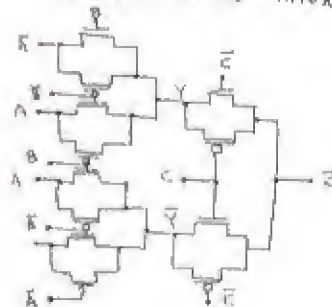
54

a) Need $\bar{Y} = AB + \bar{A}\bar{B}$. In direct analogy to Fig 10.31:



(Next)

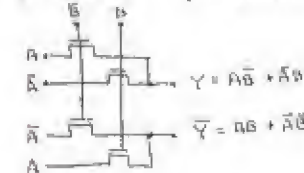
b) Need $Z = \bar{Y}C + Y\bar{C}$, where $Y = \bar{Y} = \overline{(AB + \bar{A}\bar{B})}$, whence $Y = \bar{A}\bar{B} + AB = (A + \bar{B})(\bar{A} + B) = \bar{A}\bar{B} + AB$.



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Need a CPL circuit for $Y = AB + \bar{A}\bar{B}$ and

$$\bar{Y} = AB + \bar{A}\bar{B} \quad \{\text{See Exercise 13.9b}\}$$

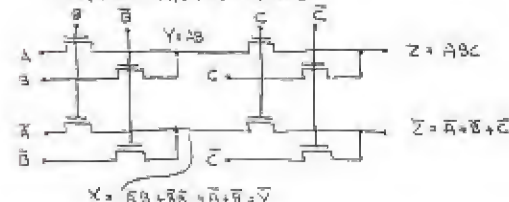


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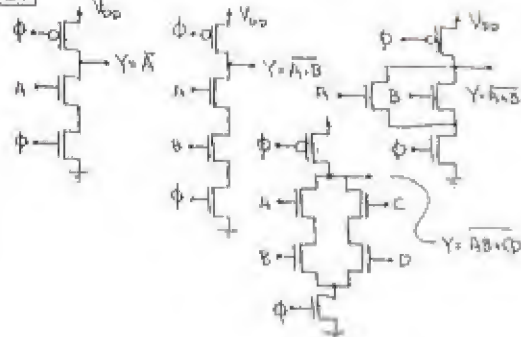
10

Require a CPL for $Z = ABC$ and $\bar{Z} = \bar{A}\bar{B}\bar{C} = \bar{A} + \bar{B} + \bar{C}$

Extend Fig 10.32 to 3 variables by dealing in pairs, creating $Y = AB$, then $Z = YC$ with $\bar{Y} = \bar{A} + \bar{B}$, then $\bar{Z} = \bar{Y} + \bar{C}$



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At $V_Y = 0.3V$, $i_{D1} = \frac{1}{2} \mu_n C_{ox} \left(\frac{W}{L} \right) (V_{DD} - V_Y)^2 = 181.5 \mu A$

At $V_Y = 2.7V$, $i_{D1} = \frac{1}{2} \mu_n C_{ox} \left(\frac{W}{L} \right) (V_{DD} - V_Y)^2 = 46.1 \mu A$

Thus $i_{D1} = (181.5 + 46.1) / 2 = 113.8 \mu A$

and $t_{FLH} = t_r = 15 \times 10^{-15} (2.7 - 0.3) / (113.8 \times 10^{-6}) = 216 ps$

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For 3 NMOS in series, the equivalent length is $3L_n = 3(0.8) = 2.4 \mu m$

Thus for $V_Y = 3.0V$, $i_D = \frac{1}{2} \mu_n C_{ox} \left(\frac{W}{L} \right) (V_{DD} - V_Y)^2 = 90.8 \mu A$

and for $V_Y = 1.5V$, $i_D = \frac{1}{2} \mu_n C_{ox} \left(\frac{W}{L} \right) (V_{DD} - V_Y)^2 = 81.6 \mu A$

Thus $i_{D1} = (90.8 + 81.6) / 2 = 86.2 \mu A$

and $t_{PHL} = 15 \times 10^{-15} (3.0 / 2) / (86.2 \times 10^{-6}) = 261 ps$

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a) $C_1 = 55 fF$

Now, for V_{G1} rising to $V_{DD} - V_t = 5 - 1 = 4V$, and assuming Q_1 continues to conduct, V_Y will fall by an amount $(C_1 / C_L) (V_{G1} - 5/30/4) = 0.67V$ to $5.0 - 0.67 = 4.33V$. Since this exceeds V_{th} , the assumption that Q_1 continues to conduct is verified. Thus V_Y drops by 0.67V

Note that if the body effect is included, it will likely be impossible to raise V_{G1} to $4V$. This $0.67V$ is the largest possible change.

b) $C_1 = 106 fF$

In view of the previous analysis, assume that ultimately $V_Y = V_{G1} = V$. Now, the change in each capacitor is the same:

$Q = CV \rightarrow 10(V - 0) = 30(5 - V)$

and $10V = 150 - 30V$, $40V = 150$, and $V = 3.75V$

Thus V_Y drops by $5 - 3.75 = 1.25V$ to $3.75V$

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For a $0.5V$ change, $t = C \Delta V / I_D = 30(10^{-15}) 0.5 / 10^{-15} = 15 ns$

Since the precharge interval is much shorter than the evaluate, the period of the minimum clocking frequency can be as great as $15 ns$, for which $f_{min} = 1 / (15 \times 10^{-9}) = 67 Hz$

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In each cycle, the output must charge completely, then discharge to at least the threshold of the succeeding gate.

From Exercise 10.10, the precharge time is about $t_w = 0.4 ns$. From Exercise 10.11, the discharge time is about $t_{PHL} = 0.5 ns$.

Thus, the maximum allowed clocking frequency can be as high as $1 / (0.4 + 0.5) \times 10^{-9} = 1.1 GHz$

Chapter 11 Problems

1 For the inverters, using Eq 13.8, 11

$$V_{th} = [V_{DD} - |V_{th}| + (k_n/k_p)^{1/2} V_{th}] / (1 + (k_n/k_p)^{1/2}) \\ = (5 - 1 + \sqrt{2.5} \cdot 1) / (1 + \sqrt{2.5}) = 5.375 / 2.58 = 2.08V$$

Current from the PMOS, for which $V_{SD} = 3V$ with $V_{GS} = 2.08V$, $I_D = (100/2.5)(2/1)[(5-1)(5-2.08) - (5-2.08)^2]/2$, or $I_D = 586 \mu A$

To sustain this from the NMOS, $586 = 100(W/L)_n [(5-1)(2.08 - 2.08/2)]$, where $(W/L)_n = 5.86/6.31 = 0.932$

Thus, for Q_5, Q_6 in series, $(W/L)_{p,6} = 2(0.932) = 1.86$ and $W_5, W_6 = 1.86 \mu m$ for $L_{p,6} = 3 \mu m$.

2 Initially, the current from the PMOS (say Q_5) is essentially zero, since V_{SD} is 0. Thus, for $V_{GS} = 5V$, $I_{D,5} = \frac{1}{2}(100)(1/1)(5-1)^2 = 1400 \mu A$

Now, for $V_{GS} = V_{GS} = 2.5V$:

$$I_{D,5} = 100(4/1)[(5-1)(2.5 - 2.5/2)] = 1375 \mu A \\ I_{D,4} = (100/2.5)(2/1)[(5-1)(2.5 - 2.5/2)] = 550 \mu A$$

Thus, the average discharge current is $(1400 - 0.1375 - 550)/2 = 415 \mu A$ and $t_{PHL} = 30 \times 10^{-15} \times 2.5 / 415 = 10^{-14} \times 61.9 = 61.9 ps$

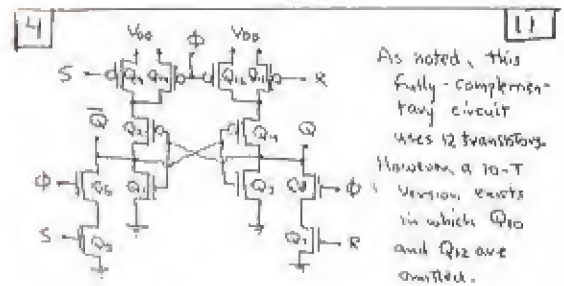
$$\text{Now, } t_{PLH} = 1.7C / (W/L)_p V_{DD} = \frac{1.7 \times 30 \times 10^{-15}}{(100/2.5)(2/1)5} = 127.5 ps$$

Thus the minimum set/reset pulse length is

$$127.5 + 61.9 = 189.4 ps$$

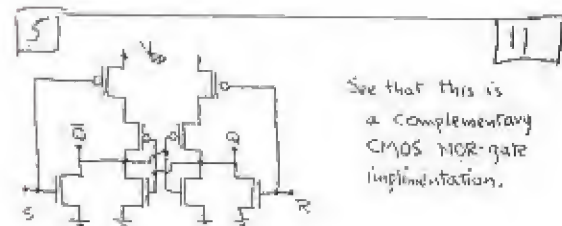
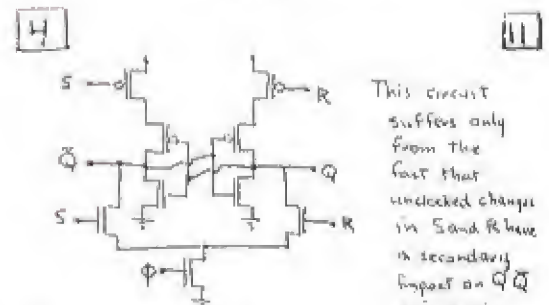
3 Assume that Q_2 is conducting, Q_1 is cut off, and Q_5 is conducting. Now to lower \bar{Q} to $V_{DD}/2 = 2.5V$, Q_2 and Q_5 must be matched, since equivalent control voltages are applied to each.

Thus $k_2 = k_5$, and $25(W/L)_2 = 25/2$, where $(W/L)_2 = (W/L)_5 = 6$



Note further that an effective 9-T version exists, in which Q_6 and Q_8 are moved below Q_5 and Q_7 , then merged into a single ground-source device. Note that all of the designs can simplify the latter idea to reduce the transistor count by 1. See the sketch following:

(next)

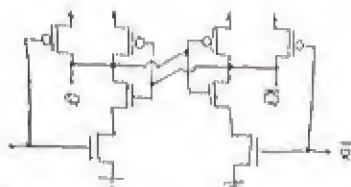


6



R	S	\bar{R}	\bar{S}	Q_{n+1}
0	0	1	1	Q_n
0	1	1	0	1
1	0	0	1	0
1	1	0	0	not defined

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In this circuit, \bar{R} and \bar{S} are high. Either going low forces the corresponding output to go high. [Thus, $\bar{S}=0 \rightarrow S=1 \rightarrow Q=1$]

If both \bar{S} and \bar{R} are low, the outputs Q and \bar{Q} are no longer complementary, but are both high. Following this, the output retains the state defined by the last of \bar{R}, \bar{S} to go high. If both \bar{R} and \bar{S} go high simultaneously, the outputs Q and \bar{Q} oscillate, initially in phase, with a phase difference, initiated by noise, which

6

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grows increasingly rapidly until the outputs "snap" into a complementary state of 0/1 or 1/0. During the oscillation, the period is somewhat less than twice the propagation delay of the basic inverter, and the amplitude is a fraction of the full logic swing. This fraction depends on the ratio of propagation time to transition time of the inverters, being larger for faster logic transitions and longer pure propagation delays. Generally speaking, the outputs are usually heavily sinusoidal.

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Note that the devices are matched, with $k_n = k_p = 20(\mu A/V^2)$, and $|V_t| = 1V$.

For $V_x = 0V, 5V$: one device is on, one off; $V_0 = 5V, 0V$

For $V_x = 1V, 4V$: one on, one off; $V_0 = 5V, 0V$

For $V_x = 1.5V, 3.5V$: one in saturation, one in triode mode.

$$I_0 = \frac{1}{2}(40)(1.5-1)^2 = 40[(5-1.5)V_0 - V_0^2/2]$$

$$\text{thus } 0.125 = 2.5V_0 - V_0^2/2$$

$$\text{or } V_0^2 - 5V_0 + 0.25 = 0$$

$$\text{and } V_0 = \frac{(-(-5) \pm \sqrt{(-5)^2 - 4(0.25)})}{2} = \frac{(5 \pm 4.984)}{2} = 0.05V$$

$$\text{Thus } V_0 = 0.05V \text{ or } 4.95V$$

For $V_x = 2.5V, 3.0V$:

$$V_2(2-1)^2 = (2-1)V_0 - V_0^2/2$$

$$\text{or } (2-1)^2 = 2.5V_0 - V_0^2/2$$

$$\text{and } V_0^2 - 4V_0 + 1 = 0$$

$$\text{where } V_0 = \frac{(-(-4) \pm \sqrt{(-4)^2 - 4(1)})}{2} = \frac{(4 \pm 2.464)}{2} = 0.27V$$

$$\text{Thus } V_0 = 0.27V \text{ or } 4.73V$$

For $V_x = 3.25V, 3.75V$:

$$(3.25-1)^2 = 2(3.75-1)V_0 - V_0^2$$

$$1.5625 = 3.5V_0 - V_0^2$$

$$V_0^2 - 3.5V_0 + 1.5625 = 0$$

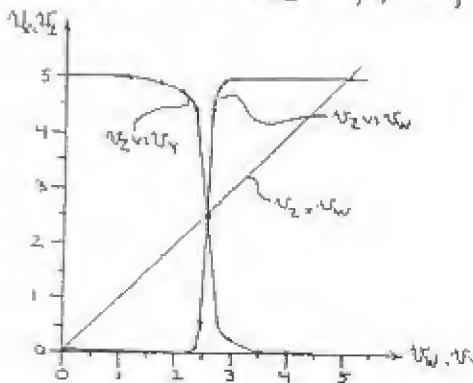
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$$\text{whence } V_0 = \frac{(-(-3.5) \pm \sqrt{(-3.5)^2 - 4(1.5625)})}{2} = \frac{(3.5 \pm 2.45)}{2} = 0.525V$$

$$\text{Thus } V_0 = 0.525V \text{ or } 4.475V$$

b. For $V_x = 2.5V, V_0 = 2.5V$ by symmetry.



Now, having plotted V_x versus V_y (or V_x versus V_0), use the graph to find V_x versus V_0 . Work backwards: first V_x , then V_y, V_x then V_0 .

For $V_x = 2.5V, V_y = V_x = V_0 = 2.5V$

For $V_x = 4.4V, V_y = 2.25V$; for $V_x = 2.25V, V_y = 2.25V$

For $V_x = 4.4V, V_y = 1.50V$; for $V_x = 1.50V, V_y = 2.65V$ (next)

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Plot these on the sketch above. See that the v_{O2} versus v_{O1} characteristic crosses the $v_{O2} = v_{O1}$ line at:

point A: (0,0)
point B: (2.5, 2.5)
point C: (5, 5)

At point B, the current flow in each inverter is:
 $I_D = \frac{1}{2}(40)(2.5-1)^2 = 45 \mu A$
where for each transistor, $\beta_0 = 100/(45 \times 10^{-6}) = 2.22 \text{ mA}$
and $g_m = 2(1/2)(40)(2.5-1) = 60 \mu A/V$

Thus for each inverter operating at (2.5, 2.5), the voltage gain is $-(g_m/g_{m1})(V_{O1}/V_O) = -g_m V_O = -60 \times 10^{-6} \times 2.5 = -150 \text{ V/V}$
Thus an estimate of the slope of the v_{O2} versus v_{O1} curve at B is $(150)^2 = 1.7 \times 10^4 \text{ V/V}$

Correspondingly a lower bound on the width of the transition region is $(5-0)/(1.7 \times 10^4)$, or 0.29 mV , that is $\pm 0.14 \text{ mV}$ around 2.5 V .

Alternatively, a more detailed analysis can be done in a number of ways. For example, consider a sample-point analysis:
From earlier work above, for $v_{O2} = 4.95 \text{ V}$, $v_{O1} = 1.5 \text{ V}$. Now to produce $v_{O2} = v_{O1} = 1.5 \text{ V}$, v_{O1} must be around 2.5 V with a value determined by

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the PMOS in saturation and the NMOS in triode mode sharing the current I_D :
Thus $I_D = \frac{1}{2}(40)(5-V_O-1)^2 = 40[(V_O-1)(5-1.5)/2]$
or $(4-V_O)^2 = 2(V_O-1)(5-1.5)$
or $16-8V_O+V_O^2 = 3V_O-3-1.25$
or $V_O^2 - 11V_O + 21.25 = 0$
whence $V_O = \frac{11 \pm \sqrt{11^2 - 4(1)(21.25)}}{2} = 2.5 \text{ V}$

While this seems strange at first, it is simply an indicator that for $V_O = 1.5 \text{ V}$, the NMOS is actually just at the edge of saturation such that the saturation-current expression still applies, for which the saturation currents of both devices are equal when $V_{DS} = 2.5 \text{ V}$. Thus the output resistance and finite current gain must be considered (as we did earlier).

For the gain of -150 V/V found above, to produce a 1 V change in v_{O2} (from 2.5 to 1.5) would require $1/150 \text{ V}$ or 6.7 mV (or 15 mV total) on v_{O1} . Recall that this 15 mV change on v_{O1} would v_{O2} from 0.05 to 4.95 V !

We conclude that the transition region is more like 15 mV than a fraction of a mV .

Note that this approach uses a combination of large- and small-signal modelling to better approximate the large-signal nonlinearities of logic.

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The approximate transfer characteristic of each inverter passes through points: (0, 5), (2.0, 4.1), (2.42, 0.4), (5, 0).

For the linear centre segment between (2.0, 4.1) and (2.42, 0.4)

an equation is $v_{O2} = a - bv_{O1}$
Here: $4.1 = a - 2.0b$, and
 $0.4 = a - 2.42b$
Subtract: $4.7 = 0.42b \rightarrow b = 10$
Now: $4.1 = a - 2.0(10) \rightarrow a = 4.1 + 20 = 24.1$
Check: $0.4 = 24.1 - 2.42(10) \text{ V}$

Thus the middle part of the characteristic is $v_{O2} = 24.1 - 10v_{O1}$

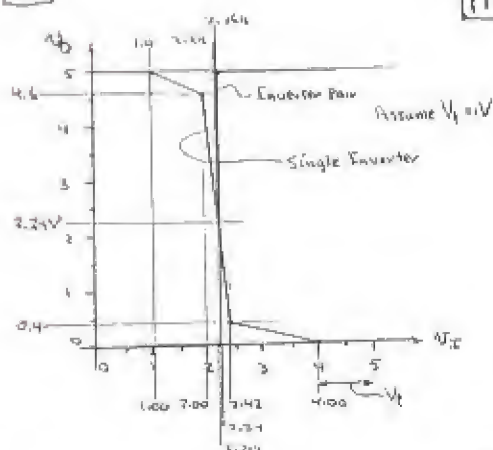
For each device, $v_{DS} = v_{GS} = V$, when $v_{O2} = 24.1 - 10v_{O1}$ or $v_{O1} = 2.41$, or $v_{O2} = 2.31 \text{ V}$, where the gain is $dv_{O2}/dv_{O1} = -10 \text{ V/V}$

Thus point B on the open-loop characteristic is $v_{O1} = v_{O2} = 2.31 \text{ V}$, where the loop gain can be approximated to be at least $(-10)^2 = 100 \text{ V/V}$

The open-loop characteristic reaches $v_{O2} = 5 \text{ V}$, where $v_{O1} = 2.316 = (5 - 2.316)/100 = 2.316 \text{ V}$ and it reaches 0 V where $v_{O1} = 2.316 - 2.316/100 = 2.314 \text{ V}$

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From Exercise 8, $T = 0.69 RC$. From the equation just preceding the exercise, a 2% error introduced by R_{on} implies that

$$R \ll R_{on} = 0.02 R$$

$$\text{and } R = R_{on}/0.02 = 1 \text{ k}\Omega/0.02 = 50 \text{ k}\Omega$$

$$\text{for which } C = T/0.69 R = 10^{-3}/(0.69 \times 50 \times 10^3) = 30 \text{ pF}$$

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From page 1025, for the monostable:

$$T = C(R + R_{on}) \ln [R/(R + R_{on}) (V_{DD}/(V_{DD} - V_{th}))]$$

Neglecting R_{on} , $T = CR \ln (V_{DD}/(V_{DD} - V_{th}))$

Now, $V_{th} = (0.5 \pm 0.1)V_{DD}$ and

$$\ln(1/(1-0.5)) = 0.693, \ln(1/(1-0.4)) = 0.916, \text{ and}$$

$$\ln(1/(1-0.6)) = 0.916$$

Thus T can vary from $(0.59/0.493)100 = 72.7\%$

to $(0.916/0.493)100 = 132.2\%$ of nominal

or by -26.3% to $+32.2\%$ of nominal.

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From Ex 13.17, $T = CR \ln [V_{DD}/(V_{DD} - V_{th}) \cdot V_{DD}/V_{th}]$

Now, for $V_{th} = V_{DD}/2$, $T = CR \ln(2 \times 2) = 1.39 CR$

b) For $f_0 = 100 \text{ kHz}$, $T = 1/f_0 = 1.39 CR$

where $CR = 0.721 \times 10^{-8}$

For a choice of $R = 10 \text{ k}\Omega$, $C = 0.721 \times 10^{-8} / 10^{-4} = 721 \text{ pF}$

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From Exercise 13.17, $T = CR \ln [V_{DD}/(V_{DD} - V_{th}) \cdot V_{DD}/V_{th}]$

For $V_{th} = 0.5V_{DD}$, $f_0 = 1/T = [CR \ln 4]^{-1} = 0.721/CR$

For $V_{th} = 0.6V_{DD}$, $f_0 = [CR \ln (10/4 \cdot 10/6)]^{-1} = 0.721/CR$

For $V_{th} = 0.4V_{DD}$, $f_0 = [CR \ln (10/6 \cdot 10/4)]^{-1} = 0.721/CR$

Thus, for V_{th}/V_{DD} over the range 0.4 to 0.6,

f_0 varies from $(0.701/0.721)100 = 97.2\%$

of nominal, through nominal to 107.2%

of nominal again.

Note that the frequency is relatively constant, independent of V_{th} variation. This is due to compensation of one half-cycle by the next, each hanging quite strongly but in opposite directions.

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$$T = C(R + R_{on}) \ln [R/(R + R_{on}) \cdot V_{DD}/(V_{DD} - V_{th})]$$

$$= 0.001 \times 10^{-6} (10^4 + 200) \ln [10^4/(10^4 + 200) \cdot 10/(10 - 5)]$$

$$= 1.02 \times 10^{-6} \ln 1.16 = 1.04 \times 10^{-6} \text{ s} = 1.04 \mu\text{s}$$

Now, $\Delta V_1 = V_{DD}R/(R + R_{on}) = 10 \times 10^4/(1.02 \times 10^4) = 9.80 \text{ V}$

and $\Delta V_2 = V_{DD} - V_{th} - V_{th} = 10 - 0.5 - 5 = 4.5 \text{ V}$

Change in V_{01} is due to the variable current in R flowing in R_{on} .

Initially, the voltage across R_{on} is $V_{DD}R_{on}/(R + R_{on})$

Finally, it is $(V_{DD} - V_{th})R_{on}/(R + R_{on})$

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Thus, the total change is $(V_{DD}/2)R_{on}/(R + R_{on})$

or $(10/2)200/(10^4 + 200) = 0.002 \text{ V}$

The peak sinking current through G_1 occurs as v_{01} rises and current flows through R_{on} and the diode. Its peak value is

$$(V_{DD} - V_{th} - V_0)/R_{on} = (10 - 5 - 0.7)/200 = 21.5 \text{ mA}$$

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$$T = C(R + R_{on}) \ln [R/(R + R_{on}) \cdot V_{DD}/(V_{DD} - V_{th})]$$

Thus $1 = 10^6 (R + 100) \ln [R/(R + 100) \cdot 1/(1 - 0.4)]$

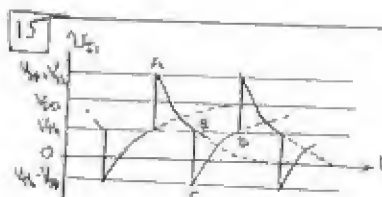
Now for R_{on} ignored:

$$R \cdot 10^6 \ln [1/0.6] = 1.958 \text{ M}\Omega$$

Clearly, for this R , R_{on} can be neglected, and $R = 1.96 \text{ M}\Omega$

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At Point A: $v_i = V_{DD} + V_{th}$, and thereafter

$$v_i = (V_{DD} - V_{th} - V_0) e^{-t/RC} + V_0$$

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At Point B: $v_i = V_{th}$ and $t = t_1$, where

$$V_{th} = (V_{DD} - V_{th}) e^{-t_1/RC} + V_0$$

or $t_1 = -RC \ln [V_{th}/(V_{DD} - V_{th})]$

or $t_1 = RC \ln [(V_{DD} + V_{th})/V_{th}]$

At Point C: $v_i = V_{th} - V_{DD}$, and thereafter

$$v_i = (V_{th} - V_{DD} - V_0) e^{-t/RC} + V_0$$

At Point D: $v_i = V_{th}$ at $t = t_2$, where

$$V_{th} = (V_{th} - 2V_{DD}) e^{-t_2/RC} + V_0$$

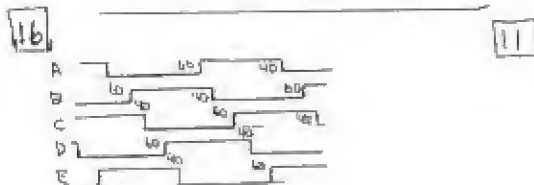
or $t_2 = -RC \ln [(V_{DD} - V_{th})/(2V_{DD} - V_{th})]$

or $t_2 = RC \ln [(2V_{DD} - V_{th})/(V_{DD} - V_{th})]$

Thus, the period $T = t_1 + t_2$

where $T = RC \left[\ln \frac{V_{DD} + V_{th}}{V_{th}} + \ln \frac{2V_{DD} - V_{th}}{V_{DD} - V_{th}} \right]$

or $T = RC \ln \left[\frac{V_{DD} + V_{th}}{V_{th}} \cdot \frac{2V_{DD} - V_{th}}{V_{DD} - V_{th}} \right]$, as suggested.



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Waveform A is low for $60 + 40 + 60 + 40 + 60 = 260\text{ns}$
and high for $40 + 60 + 40 + 60 + 40 = 240\text{ns}$

Period is $(260 + 240) = 500\text{ns}$
Frequency is $1/500 = 2\text{MHz}$

Percentage of cycle for which output is high is 48%
Check: $t_p = (60 + 40)/2 = 50\text{ns}$

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17

For 11 inverters, there are $2(11) = 22$ transitions
whose average length is $t_p = (1/2)(100\text{ns})/11 = 4.5\text{ns}$

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A 1Mb array requires 20 address bits where
 $2^n = 10^6$, or $n/\log_2 2 = 6$, $n = 6/\log_2 2 = 19.93$
Thus 20 bits are needed to address every cell.

For 16-bit words, $2^4 \times 16$ and 4 bits are not needed.
Thus $20 - 4 = 16$ bits of address are sufficient.

Check: $m = \log_{10}(10^6/16/\log_2 2) = 7.71 \times 0.301 = 2.33$
Use 16

Note: A "1Mb array" actually holds $2^{20} \times 1024 = 1048512$ cells.

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Since the array is square, there are about
 $(10^6)^{1/2}$ or 1000 word lines. More precisely
there are $(2^{10})^{1/2} = 2^5 = 32$ word lines.

For a 1-Mb square array, there are also 1024 bit lines.

Thus a straightforward design would use
1024 sense amplifiers/drivers.

Now for dynamic storage on C operating at 5V
voltage V, the dynamic power is $P_D = fCV^2$.
Thus $C = P_D/(fV^2) = 300 \times 10^{-3}/(200 \times 10^3 \times 25)$
or $C = 4000\text{pF}$

If 90% of the dynamic load is in the array, the
array capacitance is $4000(0.9) = 3600\text{pF}$
For 16 bit lines selected and active at a time,
the capacitance per bit line could be $3600/16 = 225$
which is $225/1024 = 0.22\text{pF/bit}$.

For voltage reduction to 3V, power is reduced by
a factor $3^2/5^2 = 0.36$. For the same power
level the array could be larger by a
factor $1/0.36 = 2.8$ times.

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Cell area = $1/2(21 \times 10^{-3} \times 21 \times 10^{-3})/10^3 = 0.2205\text{mm}^2$
For 2 cells, the area is 0.441mm^2 , for which
(if square) the side length is $\sqrt{0.441} = 0.663\text{mm}$
and the cell dimension is about 0.4mm by 0.8mm .

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The cell area is $10^{-9} \times 0.38 \times 10^{-6} \times 0.71 \times 10^{-6} = 0.269 \times 10^{-21}\text{m}^2$
The chip area is $19 \times 10^{-3} \times 38 \times 10^{-3} = 0.722 \times 10^{-3}\text{m}^2$
Thus the peripheral circuits and interconnect occupy
 $(0.722 - 0.269) \times 10^{-3} = 0.453 \times 10^{-3}\text{m}^2$
or $(453/722) \times 100 = 62\%$ of the chip area.

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22

For 16 blocks, 4 bits of block address are
needed. The arrays are each of $256\text{M}/16 = 16\text{Mbit}$ size. If each block array is square, it
has 4096 rows and 4096 columns. It needs
 $\log_2 4096 = 12$ bits each of row and column address
bits, for a total of $2(12) + 4 = 28$ bits/cell.

Check: $2^{28} = 268 \times 10^6$, or 256M bits.

11

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11

- a) For W high and B high, with Q originally low and the gate of Q_1 high:

$$\text{At } V_G = 2.5V, \text{ from Eq. 5.10, } V_{t1} = V_{t0} + \gamma \left[\sqrt{V_{DS1} + V_{t0}} - \sqrt{V_{t0}} \right] \\ \text{or } V_{t1} = 0.8 + 0.5 \left[\sqrt{2.5 + 0.6} - \sqrt{0.6} \right] = 1.393V$$

$$\text{Now, for } I_S = I_{D1}, \frac{1}{2} k_{n1} (V_{GS1} - V_{t1})^2 = \frac{1}{2} k_{n1} (V_{DS1} - V_{t1})^2 \\ \text{or } (W/L)_S (1.5 - 1.393)^2 = n (5 - 0.8)^2 \\ \text{or } (W/L)_S = n (4.2)^2 / 1.207^2 = 12.14$$

- b) For W high and B low, with Q originally high and the gate of Q_2 high:

At $V_G = 2.5V$, with Q_1 in saturation and Q_2 in triode:

$$\frac{1}{2} k_{n1} (5 - 0.8)^2 = k_{n2} \left[(5 - 0.8)(2.5 - 2.5/2) \right] \\ \text{or } \frac{1}{2} n (4.2)^2 = (W/L)_2 (1.75) \\ \text{or } (W/L)_2 = n (4.2)^2 / (1.75) = 1.20n$$

- c) Clearly, for a very conservative design, one in which both write mechanisms work, the larger of the choices in a) & b) would be used, namely $(W/L)_S = (W/L)_2 = 12.1$ (very large!)

In practice, this design needs a lot of area, and, instead, a conservative version of b) would likely be used, with $(W/L)_S = (W/L)_2$ larger than 1.2n, say by a factor of 2, perhaps 2.4n.

d.

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For $(W/L)_1 = 12.1$ n and matched inverters:

$$k_{n1} = 50 \times 10^{-4} n = 50 \times 10^{-4} \times 2 = 100 \mu A/V^2 \\ \text{and } k'_f = 1210 \mu A/V^2$$

$$\text{For } V_G = 5V: V_{DS1} = 0 \text{ and } i_{D1} = 0, \text{ but} \\ i_{D2} = \frac{1}{2} (1210 \times 10^{-4}) (5 - 0.8)^2 = 10.7 \mu A$$

For $V_G = 2.5V$:

$$i_{D2} = 1210 \times 10^{-4} \left[(5 - 0.8)(2.5 - 2.5/2) \right] = 8.92 \mu A$$

$$\text{and } i_{D1} = 100 \times 10^{-4} \left[(5 - 0.8)(2.5 - 2.5/2) \right] = 0.74 \mu A$$

Thus, the average discharge current is $(10.7 + 0.74)/2 = 5.72 \mu A$

Thus, the discharge time is $t = 50 \times 10^{-15} \times 2.5 / 5.72 \times 10^{-6} = 13.7 ps$

For a minimum-size design with $(W/L)_1 = 2.4$ n, the

average current would be:

$$\left[(2.4 \times 10^{-4}) (10.7 + 0.74) \right] / 2 = 1.58 \mu A$$

and the time to $V_{DD}/2$ would be

$$t = 50 \times 10^{-15} \times 2.5 / 1.58 \times 10^{-6} = 79 ps$$

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- a) Initially, $I_S = \frac{1}{2} k_{n1} (V_{GS1} - V_{t1})^2 = \frac{1}{2} (50) 10^{-4} (5/2)^2 (5 - 0.8)^2$
or $I_S = 2.205 \mu A$, and $I_{D1} = 0$ since $V_{DS1} = 0$.
Thus, $I_{D2} = 2.205 - 0 = 2.205 \mu A$

- b) At the end of the interval, $V_G = 2.5V$, and
 $V_{t1} = V_{t0} + \gamma \left[\sqrt{V_{DS1} + V_{t0}} - \sqrt{V_{t0}} \right]$
 $= 0.8 + 0.5 \left[\sqrt{2.5 + 0.6} - \sqrt{0.6} \right] = 1.49V$

Correspondingly, $I_S = \frac{1}{2} (50) 10^{-4} (5/2)^2 (2.5 - 1.49)^2 = 1.075 \mu A$

Now, Q_1 is in triode mode, with
 $I_{D1} = 50 \times 10^{-4} (4/2) \left[(5 - 1)(2.5 - 2.5/2) \right] = 687.5 \mu A$

Thus $I_{D2} = 1.075 - 687.5 = -686.4 \mu A$ (negative!)

Thus we see that Q_2 is incapable of raising Q to 2.5V. This is the case even if the body effect is ignored (check this for interest!).

(You may also be interested in calculating the highest voltage to which Q can be raised.)

- c) The average value is not relevant.

- d) It is as defined here!

Note that in Exercise 11.9, $\Delta t = 19.4 ps$, during which time the voltage on the gate of Q_1 reduces, the current in Q_1 reduces, and the current in Q_2 increases, allowing Q to become more effective.

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For $V_G = 2.5V$, $V_G = 2.5V$, $V_G = 0V$:

$$i_S = \frac{1}{2} k_{n1} (V_{GS1} - V_{t1})^2 = \frac{1}{2} (50) 10^{-4} (10/2)^2 (2.5 - 1)^2 = 28 \mu A$$

However, the voltage at Q will rise due to this current when $i_{D1} = 50(4/2) \left[(5 - 1)(V_{GS1} - V_{t1}/2) \right]$.

$$\text{Thus } V_{GS1} - V_{t1} + 5.62 = 0 \\ \text{whence } V_{GS1} = (-8 \pm \sqrt{8^2 - 4(5.62)})/2 \\ = (8 \pm 6.44)/2 = 0.78V$$

This reduces i_S to $i_S = \frac{1}{2} (50) (10/2)^2 (2.5 - 0.78)^2 = 64.8 \mu A$

for which $V_{GS1}^2 - 8V_{GS1} + (0.648 \times 2) = 0$

$$\text{whence } V_{GS1} = (-8 \pm \sqrt{8^2 - 4(0.648 \times 2)})/2 \\ = 0.165V$$

$$\text{Try } V_{GS1} = (0.165 + 0.78)/2 = 0.47V$$

for which $i_S = 125(1.5 - 0.47)^2 = 133 \mu A$

$$\text{and } V_{GS1} = (8 \pm \sqrt{64 - 4(1.33 \times 2)})/2 = 0.34V$$

$$\text{Try } V_{GS1} = (0.34 + 0.47)/2 = 0.41 \approx 0.40V$$

for which $i_S = 125(1.5 - 0.40)^2 = 151 \mu A$

$$\text{and } V_{GS1} = (8 \pm \sqrt{64 - 4(1.51 \times 2)})/2 = 0.377 \approx 0.38V \\ \text{with } i_S = 150 \mu A$$

Now, for the bit-line voltage to reduce by 0.2V, it will take

$$t = (1 \times 10^{-15} \times 0.2) / (150 \times 10^{-6}) = 1.33 ns$$

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The bit-line capacitance is $[n(2n+10)] \times 24 \times 10^{-15}$

For a 5V supply and precharge to $V_{DD}/2$, there is a 2.5V change on the 50fF cell capacitor to produce a 0.1V bit-line signal.

$$\text{Thus } 0.1 = 2.5 (50 / (2n + 10 + 50))$$

$$\text{or } 2n + 10 = 4.5(50) / 0.1 = 1250$$

$$\text{or } 2n = 1180 \text{ and } n = 590 > 512$$

Thus we can use 512 rows for which log₂ 512 = 9 bits addressing is needed.

For a sense amplifier of 5x greater gain

$$0.1/5 = 125 / (2n + 10)$$

$$2n + 10 = 5(125) / 0.1 = 6250$$

$$2n = 6180 \text{ and } n = 3090 > 2048$$

To address 2048 rows requires 11 bits

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If the memory array has n columns, it has $2n$ rows and $2n^2$ cells

$$\text{Refresh time is } 2n(2n)10^{-9} = (1.00 - 0.02)8 \times 10^3$$

$$\text{whence } n = 0.02 = 8 \times 10^{-3} / 40 \times 10^{-9} = 4000$$

The corresponding memory capacity is $2n^2 = 2(4000)^2$
or 32 Mbits

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For leakage current I , the voltage change on C in time T is $V = IT/C$

Correspondingly $I = V \times C / T = 10 \times 10^{-15} / 20 \times 10^{-15}$, and the maximum leakage is $I = 20 \times 10^{-15} / 10 \times 10^{-15} = 2 \text{ pA}$

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Pattern the solution after the approach used in the solution of Example 11.3:

For the bit-line output to reach $0.4 V_{DD} = 2.0V$ from $V_{DD}/2 = 1.5V$ in 2ns for an initial bit-line signal of $0.1/2 = 0.05V$:

$$2.7 = 1.5 + 0.05 e^{t/\tau}$$

$$\text{whence } t/\tau = \ln[(2.7 - 1.5)/0.05] = 3.178$$

$$\text{and } \tau = 2/3.178 = 0.629 \text{ ns}$$

$$\text{Thus } C/G_m = 0.629 \times 10^{-9}, \text{ and } G_m = 1.615 \times 10^3 / (0.629 \times 10^{-9}) = 1.589 \times 10^6$$

$$\text{For matched inverters, } g_{m1} = g_{m2} = G_m/2 = 1.589/2 = 0.795 \text{ mA/V}$$

$$\text{Now, } g_m = k'(W/L)(V_{GS} - V_t)$$

$$\text{and } 0.795 \times 10^{-3} = 100 \times 10^{-4} (W/L) [3.0/2 - 0.8]$$

$$\text{Thus } (W/L)_n = 0.795 \times 10^{-3} / (100 \times 10^{-4}) / 0.7 = 11.36$$

Now, for devices assumed to have length $L = 1 \mu\text{m}$ (or, alternatively, for each micron of device length)

$$W_n = 11.36 \mu\text{m} \text{ and } W_p = 3(11.36) = 34.1 \mu\text{m}$$

Now, for a differential input signal of 0.2V (and 0.1V on each bit-line), the response time is t , where $2.7 = 1.5 + 0.1 e^{t/0.629}$

$$\text{whence } t = 0.629 \ln(2.7 - 1.5) / 0.1 = 1.56 \text{ ns}$$

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11

For a 1Mb square array there are 1024 rows and 1024 columns.

Thus the bit-line capacitance is $10^{-15}(1024 \times 1024)$

$$\text{or } 1.024 \text{ pF}$$

When storing a '1', the voltage on C_b is $(V_{DD} - V_t)$

$$\text{or } (5 - 1.5) = 3.5V. \text{ With precharge to } V_{DD}/2 = 2.5V,$$

the change in voltage on $C_b = 3.5 - 2.5 = 1.0V$.

For $C_b = 25 \text{ fF}$, the bit-line voltage resulting is

$$25 / (25 + 1024) \times 1 = 23.6 \text{ mV}$$

When storing a '0', the voltage on C_b is 0V and

the change is $2.5 - 0 = 2.5V$ with a resulting bit-line signal of $25 / (25 + 1024) \times 2.5 = 58.9 \text{ mV}$

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11

Note that for the inverters,

$$k_n = k_n'(W/L)_n = 100(6/1.5) = 400 \mu A/V^2$$

$$k_p = k_p'(W/L)_p = (100/2.5)(15/1.5) = 400 \mu A/V^2$$

Thus we see that the inverters are matched.

Generally, $i_D = \frac{1}{2} k_n (V_{GS} - V_t)^2$ and

$$q_m = 2C_0/V_{GS} = k_n(V_{GS} - V_t)$$

$$\text{Now, at } V_{GS} = V_B = V_{DD}/2 = 3.3/2 = 1.65V$$

$$q_m = 400(1.65 - 0.8) = 340 \mu A/V$$

$$\text{Thus } G_m = q_m + q_p = 2(170) = 680 \mu A/V$$

For a bit-line capacitance of $0.8 pF$, $\tau = C/G_m$

$$\text{or } \tau = 0.8 \times 10^{-12} / 680 \times 10^{-6} = 1.176 \mu s$$

Now, for $0.9 V_{DD}$ reached in 2τ for a signal ΔV ,

$$0.9(3.3) = 1.65 + \Delta V e^{2\tau/\tau}$$

$$\text{or } \Delta V = (2.97 - 1.65) / 5.477 = 0.241V$$

Thus the initial voltage between bit lines

$$\text{must be } 2(0.241) = 0.482V$$

If an additional 1τ is allowed: $\tau = 2\tau = 2.35 \mu s$

$$\text{and } \Delta V = (2.97 - 1.65) / e^{2.35/\tau} = 0.107V$$

allowing a signal to be used of $2(0.107) = 0.214V$

Now, with the original bit-line signal of $0.214V$ and a delay of 3τ ;

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11

$$2.97 = 1.65 + 0.214 e^{3\tau/\tau}$$

$$\text{and } e^{3\tau/\tau} = (2.97 - 1.65) / 0.214 = 5.477$$

$$3\tau/\tau = \ln(5.477) = 1.7006$$

$$\text{where } \tau = 3/1.7006 = 1.764 \mu s$$

$$\text{Thus } C = G_m \tau = 680 \times 10^{-6} \times 1.764 \times 10^{-6} = 1.20 pF$$

This is an increase (from $0.8 pF$) of $(\frac{1.2 - 0.8}{0.8}) 100 = 50\%$

For the longer line, the initial delay to establish a suitable signal becomes 150% of $5\tau = 7.5 \mu s$

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11

a) For an initial difference between bit lines of ΔV , each bit-line signal is $\Delta V/2$.

For the rising line: $v_B = V_{DD}/2 + (\Delta V/2) e^{t/(C/G_m)}$

$$\text{where } e^{t/(C/G_m)} = (2/\Delta V)(0.9 - 0.5)V_{DD} = 0.8V_{DD}/\Delta V$$

Taking base-e logarithms and cross-multiplying,

$$t = \tau \ln(0.8V_{DD}/\Delta V) \text{ as stated.}$$

b) For a reduction of t_d to $1/2$ the original value, G_m must be doubled. To do this, double the width of all transistors (or increase by a factor of 2.02)
(next)

32

11

c) Now, for $V_{DD} = 5V$, $\Delta V = 0.2V$, with the original design, $t_d = C_0/G_m \ln(0.8(5)/0.2)$
or $t_d = 3.00 C_0/G_m$

For the modified design, $\Delta V = 0.2/4 = 0.05V$
and $t_d = C_0/G_m' \ln(0.8(5)/0.05) = 4.38 C_0/G_m'$

For these to be equal, $3.00/G_m = 4.38/G_m'$
and $G_m' = 1.46 G_m$

Thus the transistors must be made 46% wider (or be increased by a factor of 1.46)

33

11

For the DRAM arrangement, the signal is applied to only one side. Thus in comparison to the SRAM treatment, the applied signal is only half as large.

Now, the specification must be met for either a '0' or a '1' stored. The worst case is a differential signal of $40mV$ (corresponding to a single-side signal of $20mV$)

Thus $2.0 = 20 \times 10^{-3} e^{5\tau/\tau}$, and $5 = \tau \ln(2/20 \times 10^{-3})$,
or $5 = \tau \ln(100) = 4.605 \tau$, where $\tau = 1.086 \mu s$
(next)

33

11

For a $1pF$ bit-line capacitance, $G_m = C/\tau$
or $G_m = 1 \times 10^{-12} / 1.086 \times 10^{-6} = 0.921 \mu A/V$,
with $0.921 = 0.46 \mu A/V$ from each transistor.

Now, for the n-channel device, $q_m = k_n'(W/L)_n (V_{GS} - V_t)$
or $0.46 \times 10^{-6} = 100 \times 10^{-6} (W/L)_n (2.5 - 1)$

$$\text{Thus } (W/L)_n = (0.46/0.1) / 1.5 = 3.07$$

For matched inverters, $(W/L)_p = 2.5(3.07) = 7.68$

When a '1' is read, the response time will be

$$\tau = \tau \ln(2/20 \times 10^{-3}) = 1.086 \ln 100 = 5\tau$$

(Note: this is as designed!)

When a '0' is read,

$$t = 1.086 \times 10^{-6} \ln(2/100/2) = 4.01 \mu s$$

34

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$$\text{Here } 2^n = 512, n \log_2 2 = \log_2 512, n = 2.009 / 0.01 = 9.00$$

Thus the number of bits is 9

The decoder has 512 output lines, one of which is active (high). The NOR array requires true and complement input lines for each bit: $2 \times 9 = 18$

Each row uses 9 NMOS for a total of $9 \times 512 = 4608$ NMOS and 512 PMOS, for a total of 5120 transistors.

35

11

For a 256 Kbit square array, there are $(256 \times 1024)^{1/2} = 512$ rows and columns.

Number of column-address bits is $\log_2 512 = 9$.

Two multiplexers are needed, since both true and complement bit lines are required. For each multiplexer, there are 512 output lines.

For each (half) multiplexer, 512 NMOS are needed for a total of 1024 NMOS pass gates.

For the 512 output NOR decoder itself, 512 \times 403 NMOS and 512 PMOS are needed.

The address-bit inverters need 9 NMOS and 9 PMOS.

Overall, the need is for $1024 + 403 \times 9 = 5149$ NMOS and $512 + 9 = 521$ PMOS, for a total of 6122 transistors.

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11

From the solution to P11.35 above, a square 256 Kbit array has 512 rows and 512 columns for which 9 row and 9 column address bits are needed.

Check: $2^{10} = 2^{10} = 262144$.

For the tree of Fig 11.28, 9 levels of pass gates are needed.

36

11

The total number of pass gates is

$$N = 2 + 4 + 8 + 16 + 32 + 64 + 128 + 256 + 512$$

See that $N = 2 + 2(N - 512)$, or $N = 2 + 2N - 1024$, whence $N = 1022$.

Thus a tree column decoder for 9 bits needs 1022 pass transistors.

For true and complement bit lines, a total of $2(1022) = 2044$ pass transistors are needed. Compare this with the number required beyond the input inverters in P11.35 namely $6122 - 18 = 6104$.

37

11

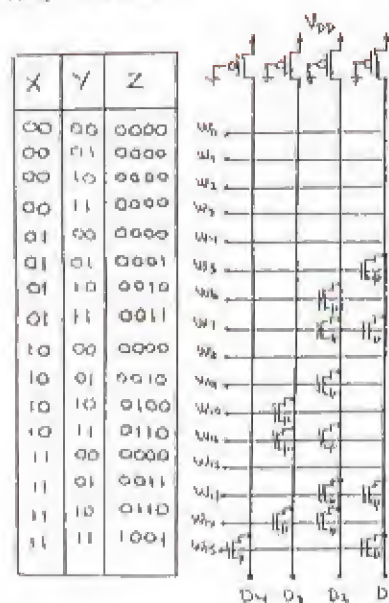
Note from Fig 11.29 that the output is high if no word is selected. Thus, logically, high must correspond to logic 0 (and no transistor was noted in the text).

Correspondingly, the words stored in Fig 11.29 are 0100, 0000, 1000, 1001, 0101, 0001, 0110, and 0010.

38

11

Need $Z = X \cdot Y$



Note that a total of 14 NMOS and 14 PMOS are used.



39

11

a) For the PMOS, with $V_0 = 2.5V$

$$I_D = (90/3) \times 10^{-4} (12/1.2) [(5-1)2.5 - 2.5^2/2] = 30 \times 10^{-4} (10) [4(2.5) - 2.5^2/2] = 2.0V$$

Thus the average charging current is 2.06mA.

Time for precharge, $t = CV/I$

$$\text{whence } t = 1 \times 10^{-11} (5-0) / (2.06 \times 10^{-3}) = 2.42$$

b) For the word-line rise, $\tau = RC = 5 \times 10^{-12} \times 2 \times 10^{-12} = 10^{-24}$

$$\text{Here, } V_W = 5(1 - e^{-t/\tau})$$

Thus the rise time (10% to 90%) is essentially the time t to 90%, where

$$0.9(5) = 5(1 - e^{-t/\tau})$$

$$e^{-t/\tau} = 0.1$$

$$\text{and } t = -\tau \ln(0.1) = 2.3\tau$$

At the end of one time constant, $t = \tau = 10ns$,

$$\text{and } V_W = 5(1 - e^{-10/10}) = 3.16V$$

$$\text{For discharge, } I_{D_{av}} = \frac{1}{2} k_n' (W/L)_n (V_{GS} - V_t)^2 = \frac{1}{2} (90)(3/1.2)(3.16-1)^2 = 525$$

$$\text{Thus, the bit-line voltage will lower by } 1V \text{ in about } \Delta t = CV/I_{D_{av}} = 1 \times 10^{-11} / (525 \times 10^{-4}) = 1.90ns$$

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(11)

(a) $V_{OH} = 0 - 0.75 = -0.75V$
 $V_{OL} = 0 - 0.75 - IR = -(0.75 + IR)$

(b) $V_{IH} = -(IR/2 + 0.75) = -(0.75 + IR/2)$

(c) For $i = 0.99 I$, $V_{OH} = 750 + 75 \Omega \cdot 0.99 = 750 \text{ mV}$
 $i = 0.01 I$, $V_{OL} = 750 + 75 \Omega \cdot 0.01 = 195 \text{ mV}$
For $0.99 I$ in Q_2 , $V_{E1} = -(0.75 + \frac{IR}{2}) = -(0.750 + 0.635)$
 $= -(0.275 + IR/2)$

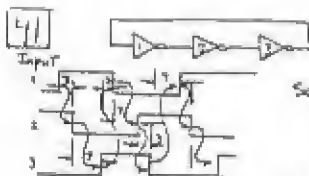
(d) For $0.01 I$ in Q_2 , $V_{E1} = -(0.75 + IR/2) + 0.115$
 $= -(0.635 + IR/2)$

(e) $V_{IH} = -(0.635 + IR/2)$
 $V_{OL} = -(0.275 + IR/2)$

(f) $NM_H = -0.75 - (0.635 + IR/2)$
 $= IR/2 - 0.115$
 $NM_L = -(0.275 + IR/2) - (0.75 + IR)$
 $= IR/2 - 0.115$

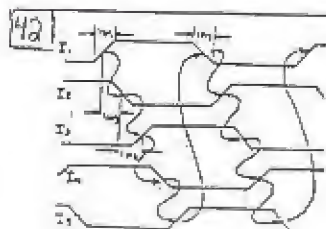
(g) $V_{IH} - V_{OL} = -(0.635 + IR/2) - (-(0.275 + IR/2))$
That is, $IR/2 - 0.115 = 0.370$
And $IR = 2(0.370) = 0.740V$

(h) $V_{OH} = -0.75V$; $V_{OL} = -0.75 - 0.19 = -0.94V$
 $V_{IH} = -(0.75 + 0.345) = -1.12V$
 $V_{IL} = -(0.615 + 0.345) = -0.96V$
 $V_E = -(0.750 + 0.245) = -1.095V$

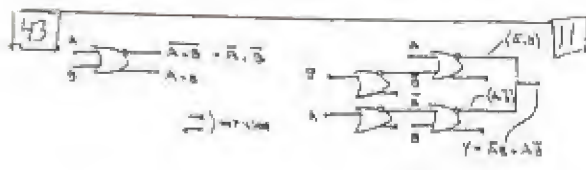


See that once started,
the process continues;
that is we have an
oscillation.

Output rises and falls.



10 transitions per cycle, each of 1ms duration:



$\boxed{44}$ For $V_{E1} + V_{E2} = -1.475V$, $I_{E1} = 2.17$, $V_{E1} = -1.7V$ $\boxed{11}$
 For $V_{E1} + V_{E2} = -1.7V$, $I_{E1} = 24.00mA$, $V_{E1} = -1.5V$
 For $V_{E1} + V_{E2} = -1.650V$, $I_{E1} = 4.12mA$, $V_{E1} = -0.87V$
A.4.4 : $I_{B1} = 0.01 (2.17) = 2.17\mu A$ $V_{E1} = \frac{30 \times 10^{-3}}{2.17 \times 10^{-6}} = 1380V$
 $I_{B1} = 0.01 (2.17) = 2.17\mu A$ $V_{E1} = \frac{30}{2.17} = 13.8V$
 $I_{E2} = \frac{2 \times 1.7}{10} = 0.34mA$ $V_{E2} = \frac{2 \times 1.7}{10} = 0.34V$
 and $R_{in2} = 10(20 + 50) = 5.5k\Omega$
 $\therefore \text{gain} = \frac{30}{20 + 50} \times (5.5k\Omega \parallel 10k\Omega) \times \frac{100}{101} = \frac{1}{101} \times \frac{1}{20 + 50} = \frac{0.73}{101}$
A.4.5 : $I_{B1} = I_{B2} = 2\mu A$ $V_{E1} = \frac{30}{2} = 15V$
 $I_{E2} = \frac{2 \times 10}{10} = 0.2mA$ $V_{E2} = 0.2V$
 and $R_{in2} = 10(20 + 10) = 3.3k\Omega$
 $\therefore \text{gain} = \frac{30}{20 + 10} \times (3.3k\Omega \parallel 10k\Omega) \times \frac{100}{101} = \frac{1}{101} \times \frac{1}{20 + 10} = \frac{2.74}{101}$
A.4.6 : $I_{B1} = 0.94(4.12) = 3.91\mu A$ $V_{E1} = \frac{30}{3.91} = 7.67V$
 $I_{B1} = 0.31(4.12) = 1.28\mu A$ $V_{E1} = \frac{30}{1.28} = 23.4V$
 $I_{E2} = \frac{2 \times 4.12}{10} = 0.824mA$ $V_{E2} = 0.824V$
 and $R_{in2} = 10(20 + 10) = 3.3k\Omega$
 $\therefore \text{gain} = \frac{30}{20 + 10} \times (3.3k\Omega \parallel 10k\Omega) \times \frac{100}{101} = \frac{1}{101} \times \frac{1}{20 + 10} = \frac{0.73}{101}$

115 Assume I_E is constant at 4 mA .

(2) Currents are: 3.6 mA and 2.4 mA

\therefore Emitter-Base voltage difference $= V_T \ln \frac{3.6}{2.4}$

$\sigma = 25 \ln 1.5 = 54.9\text{ mV}$

Thus $V_{E1} = -1.72 - 0.055 = -1.775\text{ V}$

$V_{E2} = -1.72 + 0.055 = -1.665\text{ V}$

(3) Currents are: $4(0.999) = 3.996\text{ mA}$ and $0.001 \times 4 = 4\text{ }\mu\text{A}$

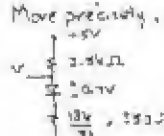
\therefore Emitter-Base voltage difference $= V_T \ln \frac{3.996}{0.001}$

$\sigma = 25 \ln 3996 = 173\text{ mV}$

Thus $V_{E1} = -1.72 - 0.073 = -1.793\text{ V}$

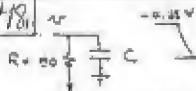
$V_{E2} = -1.72 + 0.073 = -1.647\text{ V}$

46 $I_{OL} = \frac{2-1.7}{50} = 4.6 \mu A$ 11
 $P_D = 2(4.6) = 9.2 \mu W$
 $I_{OH} = \frac{2-0.7}{50} = 22.4 \mu A$
 $P_D = 2(22.4) = 44.8 \mu W$
 For the logic-gate case $P_D = 4 \mu A \times 5.2 V = 20.8 \mu W$
 Thus total $P_D = 9.2 + 44.8 + 20.8 = 74.8 \mu W$
 (ignoring R_D)

50 $V_{OL} \approx 0.7 V$; $V_{OH} = +5.0 V$
 More precisely, for $V_{OL} = v$:

 $v = \frac{0.353}{2.5 + 0.353} \cdot (5 - 0.7) = 0.7 + 1$
 ie $V_{OL} = 1.73 V$
 Logically: A is high if one of A or B is one of C or D are high.
 That is $A = (A+B) \cdot (C+D)$

47 $V_{NH} = 0.85 V$, of which 50% is 132 mV. 11
 for $\beta = 100$ and $V_{BE2} = 0.85 V$, $I_{E2} = 22.4 \mu A$.
 Approximately:
 $-2 + \frac{50}{50 + \frac{20}{\beta+1}} \cdot (2 - 0.85) = -0.88 - 0.72$
 $\frac{50(1.7)}{50 + \frac{20}{\beta+1}} = 0.47$
 $50 = \frac{2.45}{\beta+1} = 61.05$
 where $\beta = \frac{2.5}{0.04} = 62.5$
 Check: For $V_{BE} = -0.88 - 0.72 = -1.6 V$
 $I_{E2} = \frac{2 - 1.6}{50} = 8 \mu A$
 and $V_{BE} = \frac{2.5}{10} = 0.25 V = 0.25 V$ small, can ignore.

54 For $V_{E1} = V_O = V_{OH}/2 = 5/2 = 2.5 V$, 1
 $I_{OH} = \frac{1}{2} k'_n (W/L)_n (V_{GS} - V_t)^2$
 $= \frac{1}{2} (100) (10^{-4}) (2.5 - 0.7 - 1)^2 = 6.4 \mu A$
 Now, the collector current of Q_2 is $i_{C2} = i_{OH}$
 $= 100 (6.4 \times 10^{-4}) = 6.4 \mu A$
 Correspondingly, the totem-pole current is
 $i_{EQ1} = (6.4 + 6.4) \times 10^{-4} = 12.8 \mu A$
 Now, for $i_{EQ1} = i_{EQ2}$, $i_{OP} = i_{ON} = 6.4 \mu A$
 Thus $6.4 = \frac{1}{2} (100/2.5) (W/L)_p (5 - 2.5 - 0.7 - 1)^2$
 where $(W/L)_p = 2.5 (2/A) = (5 \mu m / \mu m)$
 Note that the latter could be seen directly!

48  11
 $v = -0.88 + (1.2 - 2)(1 - e^{-0.88})$
 or $v = -2 + 0.12 e^{-v/500}$
 After this, $v = -1.77 V$
 ie $-1.77 = -2 + 0.12 e^{-v/500}$
 or $e^{-v/500} = \frac{2 - 1.77}{0.12} = 1.92$ and $-1/500 = -1.573$
 Thus $C = \frac{10^{-9}}{50(1.573)} = 12.6 \times 10^{-12} = 12.6 pF$

52 At the threshold V_{th} , $V_G = V_E = V_{th} = v$, and the two MOS operate in saturation with equal currents. Thus $\frac{1}{2} (100/2.5) (2.5 - v - 0.7 - 1)^2 = \frac{1}{2} (100) (2.5 - v)^2$
 Thus, $(2.5 - v)^2 = 2.5 (v - 1.7)^2$
 and $(2.5 - v) = \sqrt{2.5} (v - 1.7)$
 Usefully, $(2.5 - v) = (1.58 V - 2.69)$
 where $2.58 V = 5.99$, and $v = V_{th} = 3.32 V$
 For this value, $i_{OH} = \frac{1}{2} (100) (2.5) (2.5 - 0.7 - 1)^2 = 38.4 \mu A$
 and the totem-pole current is $(2 + 1) i_{OH}$
 or $101 (38.4) \times 10^{-6} = 3.88 \mu A$

49 $\Delta V = 4.5 \times 30 \times 10^{-3} = 20 \text{ mV}$ 11
 Rise Time = $\frac{5}{1} = 5 \mu s$
 Return Time = $\frac{2.5}{20} = 0.125 \mu s$
 $L = \frac{2.5 \text{ nH} \times 20 \text{ cm/s}}{5 \times 2} = 7.5 \text{ cm}$

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The problem as stated is very general, and, correspondingly, its solution can be long and complex. Assume for simplicity that the specifications of Problem 11.57e apply, with matched MOS having $(W/L)_p = 2.5(W/L)_n$.

For R_2 : With $V_{D1} = V_{t1} = V_t = 0.772V$
 $I_{D1} = 100(10^{-4})(3/4)[(5-0.772)(0.772-0.772/2)] = 209 \mu A$
 Now, if 50% of this is lost in R_2 ,
 $R_2 = 0.7 / (0.50 \times 209) = 6.70 k\Omega$
 Now if 20% is lost in R_2 ,
 $R_2 = 0.7 / (0.20 \times 209) = 16.7 k\Omega$

For R_1 :

$I_{D1} = 100(10^{-4})(3/4)(2.5)(2/1)[(5-0.772)(0.772-0.772/2)] = 256 \mu A$
 Now, if 50% of this is lost in R_1 ,
 $R_1 = (5-0.772) / (0.50 \times 256) = 36.5 k\Omega$
 Now, if 20% is lost in R_1 ,
 $R_1 = 2.5(36.5) = 91.1 k\Omega$

In comparison:

For the 50% case, $R_1/R_2 = 36.5/6.70 = 5.45$
 For the 20% case, $R_1/R_2 = 91.1/16.7 = 5.45$
 (Why should their equality be obvious?)
 Thus, in general $R_1/R_2 = 5.45$

55

For the circuit in Fig 11.45e, $R_1 = R_2 = 5k\Omega$ robs the base of some of its drive current, namely $0.7/5 \times 10^3 = 140 \mu A$. Using results from the solution of P11.52, above:

For t_{PLH} : $I_{D1} = 595 - 140 = 455 \mu A$
 and $I_{D2} = 101(455 \times 10^{-6}) = 46.0 \mu A$
 Thus $t_{PLH} = 2 \times 10^{-12} \times 2.5 / 4.6 \times 10^{-5} = 108.7 ps$

For t_{PHL} : $I_{D1} = 977 - 140 = 837 \mu A$
 and $I_{D2} = 101(837 \times 10^{-6}) = 84.5 \mu A$
 Thus $t_{PHL} = 2 \times 10^{-12} \times 2.5 / 84.5 \times 10^{-5} = 59.3 ps$
 Thus $t_p = (59.3 + 108.7) / 2 = 84 ps$

56

For the BiCMOS NAND of Fig 11.47 to have a dynamic response somewhat like that of the inverter of Fig 11.45e:

$$(W/L)_{pA} + (W/L)_{pB} = (W/L)_p$$

$$\text{and } (W/L)_{nA} + (W/L)_{nB} = 2(W/L)_n$$

61

For t_{PLH} :

At $V_{D1} = 0V$, $I_{D1} = 1/2(100/2.5)(3/4)(5-0-1) = 640 \mu A$
 At $V_{D1} = 2.5V$, $I_{D1} = 100(3/4)(2.5)(2.5-2.5/2) = 550 \mu A$
 Thus $I_{D1av} = (640 + 550) / 2 = 595 \mu A$
 and $I_{D2} = 100(1)595 = 60.1 \mu A$

Thus $t_{PLH} = CV/S = 2 \times 10^{-12} \times 2.5 / (60.1 \times 10^{-5}) = 83.2 ps$

For t_{PHL} :

At $V_{D1} = 5.0V$, $I_{D1} = 1/2(100/2.5)(3/4)(5-0.7-1) = 1.09 mA$
 At $V_{D1} = 2.5V$, $I_{D1} = 100(3/4)[(5-0.7-1)(2.5-0.7)] = 864 \mu A$
 Thus $I_{D1av} = (1089 + 864) / 2 = 977 \mu A$
 and $I_{D2} = 101(977 \times 10^{-6}) = 98.6 \mu A$

Thus $t_{PHL} = CV/S = 2 \times 10^{-12}(2.5) / (98.6 \times 10^{-5}) = 50.7 ps$

Thus $t_p = (83.2 + 50.7) / 2 = 67.0 ps$

Note that this solution embodies two assumptions:

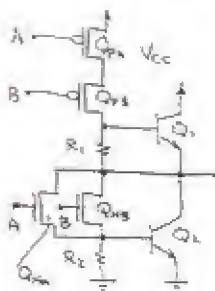
- 1) Internal capacitances can be neglected.
- 2) Transitions are from ideal 0V and 5V output-signal levels.

If outputs of $(5-0.7) = 4.3V$ and $(0.7-1) = -0.3V$ apply, t_p becomes about

$$67.0(2.5-0.7)/2.5 = 48 ps$$

67

A BiCMOS 2-input NOR is as shown:



In terms of the basic matched inverter:

$$(W/L)_{pA} + (W/L)_{pB} = 2(W/L)_p$$

$$(W/L)_{nA} + (W/L)_{nB} = (W/L)_n$$

where $(W/L)_p$ and $(W/L)_n$ characterize the inverter.

CHAPTER 12 - PROBLEMS

12.1

$$T(s) = \frac{\omega_0}{s + \omega_0} \quad T(j\omega) = \frac{\omega_0}{j\omega + \omega_0}$$

$$|T(j\omega)| = \frac{\omega_0}{\sqrt{\omega_0^2 + \omega^2}}$$

$$\phi(\omega) \triangleq \tan^{-1} \left[\frac{\text{Im}(T(j\omega))}{\text{Re}(T(j\omega))} \right]$$

$$= -\tan^{-1} \omega/\omega_0$$

$$G = 20 \log_{10} |T(j\omega)|$$

$$A = -20 \log_{10} |T(j\omega)|$$

ω	$ T(j\omega) $ [V/V]	G [dB]	A [dB]	ϕ °
0	1	0	0	0
0.5 ω_0	0.8944	-0.97	0.97	-26.57
ω_0	0.7071	-3.01	3.01	-45.0
2 ω_0	0.4472	-6.99	6.99	-63.43
5 ω_0	0.1961	-14.1	14.1	-78.69
10 ω_0	0.0995	-20.0	20.0	-84.29
100 ω_0	0.010	-40.0	40.0	-89.43

12.2

$$T(s) = \frac{1}{(s+1)(s^2+s+1)}$$

$$= \frac{1}{s^3 + 2s^2 + 2s + 1}$$

$$T(j\omega) = \left[j(2\omega - \omega^3) + (1 - 2\omega^2) \right]^{-1}$$

$$|T(j\omega)| = \left[(2\omega - \omega^3)^2 + (1 - 2\omega^2)^2 \right]^{-1/2}$$

$$= \left[4\omega^2 - 4\omega^4 + \omega^6 + 1 - 4\omega^2 + 4\omega^2 \right]^{-1/2}$$

$$= \left[1 + \omega^4 \right]^{-1/2}$$

$$= \frac{1}{\sqrt{1 + \omega^4}}$$

For Phase Angle:

$$\phi(\omega) = \tan^{-1} \left[\frac{\text{Im}[T(j\omega)]}{\text{Re}[T(j\omega)]} \right]$$

$$= -\tan^{-1} \left[\frac{2\omega - \omega^3}{1 - 2\omega^2} \right]$$

For $\omega = 0.1$:

$$|T(j\omega)| = (1 + 0.1^4)^{-1/2} \approx 1$$

$$\phi(\omega) = -11.5^\circ = \underline{\underline{-0.20 \text{ rad}}}$$

For $\omega = 1 \text{ rad/s}$:

$$|T(j\omega)| = (1 + 1^4)^{-1/2} = 1/\sqrt{2} = \underline{\underline{0.7}}$$

$$\phi = -\tan^{-1}(1/-1) = -135^\circ = \underline{\underline{2.356}}$$

Note: $G = -3 \text{ dB}$

Also: $\tan^{-1}(-1) = -45^\circ$ or -135°
 $\tan^{-1}(-1/1) = -45^\circ$
 $\tan^{-1}(1/-1) = -135^\circ$

For $\omega = 10 \text{ rad/s}$:

$$|T(j\omega)| = (1 + 10^4)^{-1/2} = \underline{\underline{0.001}}$$

$$\phi = -\tan^{-1} \left[\frac{2(10) - 10^3}{1 - 2(10^2)} \right]$$

CONT.

$$\begin{aligned}
 &= -\tan^{-1} \left[\frac{-980}{-199} \right] \\
 &= - \left[180^\circ + \tan^{-1} \left(\frac{980}{199} \right) \right] \\
 &= -258.5^\circ \\
 &= \underline{\underline{4.512 \text{ rad}}}
 \end{aligned}$$

Now consider an input of $A \sin \omega t$ to $T(s)$. The output is then given by:

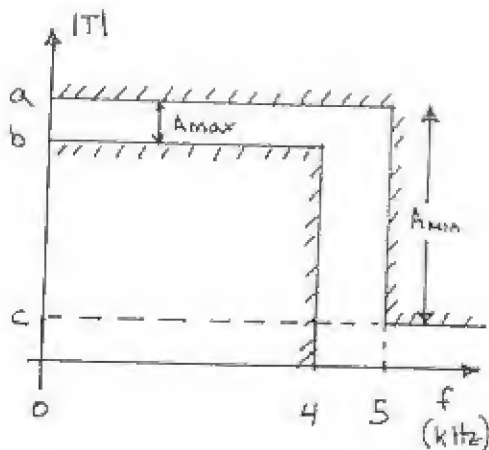
$$A |T(j\omega)| \sin(\omega t + \phi(\omega))$$

Using this result, the output to each of the following inputs will be:

INPUT	OUTPUT
$2 \sin(0.1t)$	$2 \sin(0.1t - 0.2)$ i.e. $2 \times 1 = 2$
$2 \sin(1t)$	$\sqrt{2} \sin(t - 2.356)$ i.e. $2 \times \frac{1}{\sqrt{2}} = \sqrt{2}$
$2 \sin(10t)$	$2 \times 10^{-3} \sin(10t - 4.512)$

12.3

12.4



Note $|T|$ is shown in a linear scale but A_{\max} and A_{\min} are in dB

From the problem

$$\frac{a}{b} = 1.1, \quad c = 0.1\% a \text{ or } \frac{c}{a} = 0.001$$

$$A_{\max} = 20 \log_{10} a - 20 \log_{10} b$$

$$= 20 \log_{10} \frac{a}{b}$$

$$= 20 \log_{10} (1.1)$$

$$= \underline{\underline{0.83 \text{ dB}}}$$

$$A_{\min} = 20 \log_{10} a - 20 \log_{10} c$$

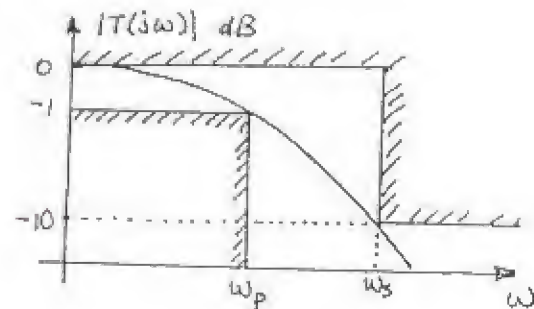
$$= 20 \log_{10} \left(\frac{a}{c} \right)$$

$$= 20 \log_{10} (0.001)$$

$$= \underline{\underline{60 \text{ dB}}}$$

$$\text{Selectivity} = \frac{\omega_s}{\omega_p} = \frac{2\pi 5}{2\pi 4} = \underline{\underline{1.25}}$$

12.5



$$T(s) = \frac{k}{1+s\tau}$$

$$= \frac{1}{1+s}$$

If $\tau = 1s$ & the DC gain = 1 then $\underline{\underline{k=1}}$

$$|T(j\omega)| = \frac{1}{\sqrt{1+\omega^2}}$$

At the passband edge :

CONT.

$$|T(j\omega_p)| = \frac{1}{\sqrt{1+\omega_p^2}} = 10^{-1/20}$$

$$\therefore \omega_p = \underline{0.5088 \text{ rad/s}}$$

At the stopband edge:

$$|T(j\omega_s)| = \frac{1}{\sqrt{1+\omega_s^2}} = 10^{-10/20}$$

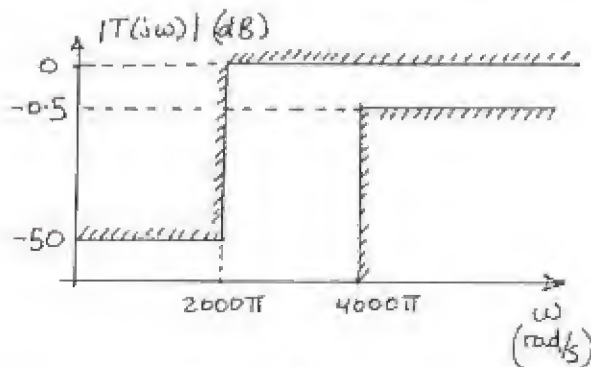
$$\therefore \omega_s = \underline{3 \text{ rad/s}}$$

$$\text{Selectivity} = \frac{\omega_s}{\omega_p} = \frac{3}{0.5088} = \underline{5.9}$$

12.6

Passband is defined by: $f \gg 2 \text{ kHz}$
 $\Rightarrow \omega_p = 2\pi(2000) \text{ rad/s}$

Stopband is defined by: $f \leq 1 \text{ kHz}$
 $\Rightarrow \omega_s = 2\pi(1000) \text{ rad/s}$



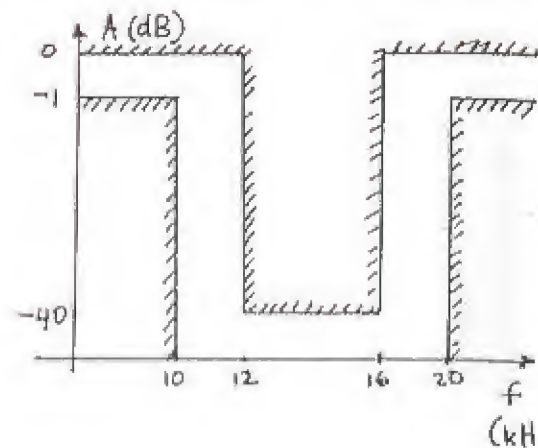
Note we assumed a maximum transmission of 0 dB.

12.7

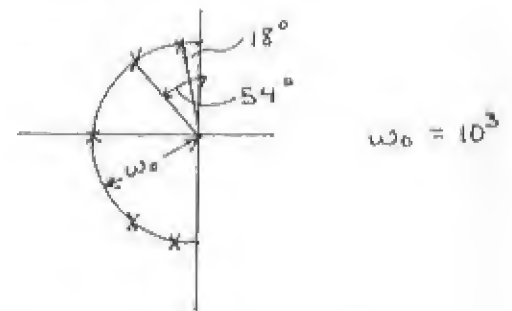
Passband: $f \in \{[0, 10 \text{ kHz}] \cup [20 \text{ kHz}, \infty]\}$

Stopband: $f \in [12 \text{ kHz}, 16 \text{ kHz}]$

$$A_{\max} = 1 \text{ dB}, A_{\min} = 40 \text{ dB}$$



12.8



Poles at 18° :

$$\begin{aligned} P_1 &= \omega_0 (-\cos(90^\circ - 18^\circ) \pm j \sin(90^\circ - 18^\circ)) \\ &= \omega_0 (-\cos 72^\circ \pm j \sin 72^\circ) \\ &= \omega_0 (-0.309 \pm j 0.951) \end{aligned}$$

Poles at 54° :

$$\begin{aligned} P_2 &= \omega_0 (-\cos 36^\circ \pm j \sin 36^\circ) \\ &= \omega_0 (-0.809 \pm j 0.588) \end{aligned}$$

Poles on Real Axis

$$P_3 = -\omega_0$$

CONT.

Note: Given a pair of poles

$$P_1 = \omega_0 (-\cos \alpha \pm j \sin \alpha)$$

introduces a second order term as follows:

$$\begin{aligned} & (s + \omega_0 \cos \alpha - j \omega_0 \sin \alpha)(s + \omega_0 \cos \alpha + j \omega_0 \sin \alpha) \\ &= s^2 + s(\omega_0 \cos \alpha - j \omega_0 \sin \alpha + \omega_0 \cos \alpha + j \omega_0 \sin \alpha) \\ & \quad + \omega_0^2 [\cos^2 \alpha + j \cos \alpha \sin \alpha - j \cos \alpha \sin \alpha + \sin^2 \alpha] \end{aligned}$$

$$= s^2 + s(2\omega_0 \cos \alpha) + \omega_0^2$$

So for P_1 we get a term:

$$\begin{aligned} & s^2 + s(2\omega_0 0.309) + \omega_0^2 \\ &= s^2 + 0.618\omega_0 s + \omega_0^2 \end{aligned}$$

For P_2 we get:

$$s^2 + 1.618\omega_0 s + \omega_0^2$$

For P_2 : $(s + \omega_0)$

∴ The denominator of $T(s)$ is given by

$$D(s) = \frac{(s + \omega_0)(s^2 + 0.618\omega_0 s + \omega_0^2)}{(s^2 + 1.618\omega_0 s + \omega_0^2)}$$

Case (a) - If all the zeros are @ ∞ , the numerator is a constant

$$|T(0)| = \frac{k}{\omega_0^5} = 1 \quad \text{for unity gain at DC}$$

$$\therefore k = \omega_0^5$$

$$T(s) = \frac{k}{D(s)} = \frac{\omega_0^5}{D(s)}$$

where $D(s)$ is given above.

Case (b) - For all zeros at 0, the numerator is given by ks^5

$$\text{At } s=j\omega \quad |T(s \rightarrow j\omega)| = \frac{k}{1} = 1$$

$$\therefore T(s) = \frac{s^5}{D(s)}$$

12.9

Poles at -1 and $-0.5 \pm j0.8$ gives a denominator:

$$\begin{aligned} D(s) &= (s+1)(s+0.5-j0.8)(s+0.5+j0.8) \\ &= (s+1)(s^2 + 2(0.5)s + 0.5^2 + 0.8^2) \\ &= (s+1)(s^2 + s + 0.89) \end{aligned}$$

Zeros at ∞ and $\pm j2$ give a numerator:

$$N(s) = k(s+j2)(s-j2) = k(s^2+4)$$

Note there is one zero at ∞ because
Degree($D(s)$) - Degree($N(s)$) = 1

$$T(s) = \frac{k(s^2+4)}{(s+1)(s^2+s+0.89)}$$

$$|T(j0)| = \frac{k(4)}{0.89} = 1 \quad \therefore \text{DC gain} = 1$$

$$\Rightarrow k = 0.2225$$

$$\therefore T(s) = \frac{0.2225(s^2+4)}{(s+1)(s^2+s+0.89)}$$

12.10

Numerator is given by

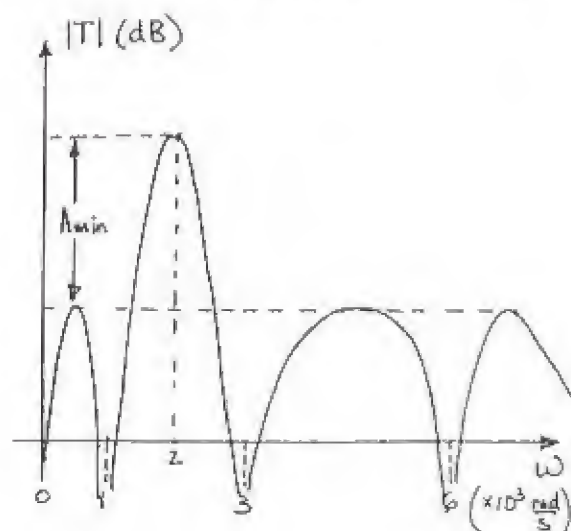
$$a_7 (s-0) (s^2 + (10^3)^2) (s^2 + (3 \times 10^3)^2) \times (s^2 + (6 \times 10^3)^2)$$

$$= a_7 s (s^2 + 10^6) (s^2 + 9 \times 10^6) (s^2 + 36 \times 10^6)$$

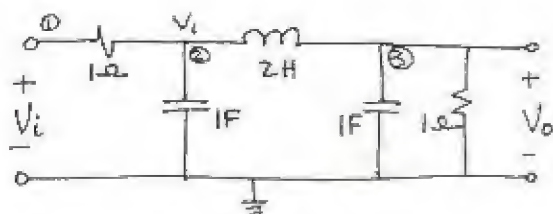
Degree of Numerator $\triangleq M = 7$ Degree of Denominator $\triangleq N$ Given that there is one zero at ∞ :

$$N - M = 1 \Rightarrow \underline{N = 8}$$

$$\therefore T(s) = \frac{a_7 s (s^2 + 10^6) (s^2 + 9 \times 10^6) (s^2 + 36 \times 10^6)}{s^8 + b_7 s^7 + b_6 s^6 + \dots + b_0}$$



12.11



The easiest way to solve the circuit is to use nodal analysis at nodes ①, ②, ③

At node ③ $\sum I = 0$

$$\frac{V_0}{1} + \frac{V_0}{1/s} + \frac{V_0 - V_1}{2s} = 0$$

$$\therefore V_1 = V_0 (2s^2 + 2s + 1) \quad \text{Eq. (a)}$$

At node ② $\sum I = 0$

$$\frac{V_1 - V_i}{1} + \frac{V_1}{1/s} + \frac{V_1 - V_0}{2s} = 0$$

$$\therefore V_1 (2s^2 + 2s + 1) = V_0 + 2s V_i \quad \text{Eq. (b)}$$

(a) \rightarrow (b)

$$V_0 (2s^2 + 2s + 1)^2 = V_0 + 2s V_i$$

$$V_0 (4s^4 + s^3(4+4) + s^2(2+4+2) + s(2+2) + 1) = V_0 + 2s V_i$$

$$\frac{V_0(s)}{V_i(s)} \triangleq T(s) = \frac{2s}{4s^4 + 8s^3 + 8s^2 + 4s}$$

$$T(s) = \frac{0.5}{s^3 + 2s^2 + 2s + 1}$$

Poles are given by:

$$s^3 + 2s^2 + 2s + 1 = 0$$

$$(s+1)(s^2 + s + 1) = 0$$

$$\therefore \text{Poles are } s = \underline{-1} \text{ and } s = \underline{-\frac{1}{2} \pm j\sqrt{3}/2}$$

12.12

$$A_{\max} = 1 \text{ dB}, A_{\min} = 20 \text{ dB}, \omega_s/\omega_p = 1.3$$

Using:

$$A(\omega_s) = 10 \log \left[1 + \epsilon^2 \left(\frac{\omega_s}{\omega_p} \right)^{2N} \right] \quad \text{Eq. (12.15)}$$

$$= A_{\min}$$

CONT

$$\epsilon = [10^{A_{\min}/10} - 1]^{1/2} = 0.5088$$

$$A_{\min} = 10 \log \left[1 + \epsilon^2 \left(\frac{\omega_s}{\omega_p} \right)^{2N} \right]$$

$$10^{A_{\min}/10} - 1 = \epsilon^2 \left(\frac{\omega_s}{\omega_p} \right)^{2N}$$

$$\log(10^{A_{\min}/10} - 1) = \log(\epsilon^2 \left(\frac{\omega_s}{\omega_p} \right)^{2N})$$

$$N = \frac{\log \left[(10^{A_{\min}/10} - 1) / \epsilon^2 \right]}{2 \log(\omega_s / \omega_p)}$$

$$= 11.3 \Rightarrow \text{choose } \underline{N=12}$$

The actual value of stopband attenuation can be calculated using the integer value of N :

$$A(\omega_s) = 10 \log \left[1 + \epsilon^2 \left(\frac{\omega_s}{\omega_p} \right)^{2N} \right]; N=12$$

$$= \underline{27.35 \text{ dB}} \quad \text{actual attenuation}$$

If the stopband specs are to be met exactly we need to find A_{\max} .

Eq. 12.15 can be rearranged to give

$$\epsilon^2 = \frac{10^{A_{\min}/10} - 1}{\left(\omega_s / \omega_p \right)^{2N}} \quad \begin{matrix} A_{\min} = 20 \\ N = 12 \end{matrix}$$

$$= 0.1824$$

$$\therefore A_{\max} = 10 \log(1 + \epsilon^2)$$

$$= \underline{0.73 \text{ dB}}$$

12.13

$$N=7, A_{\max}=3 \text{ dB}$$

We want attenuation at

$$\omega = 1.6 \omega_p \quad \text{or} \quad \frac{\omega_s}{\omega_p} = 1.6$$

$$\epsilon = \sqrt{10^{A_{\max}/10} - 1} = 0.998$$

$$A(\omega) = 10 \log \left[1 + \epsilon^2 \left(\frac{\omega}{\omega_p} \right)^{2N} \right]$$

$$= 10 \log \left[1 + 0.998^2 (1.6)^{14} \right]$$

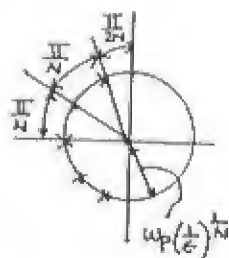
$$= \underline{28.56 \text{ dB}}$$

12.14

$$\omega_p = 10^3 \text{ rad/s}, N=5$$

$$A_{\max} = 1 \text{ dB} \Rightarrow \epsilon = 0.5088$$

Find solution graphically



$$P_1 = \omega_p \left(\frac{1}{\epsilon} \right)^{1/N} \angle \left(\frac{\pi}{2} + \frac{\pi}{2N} \right)$$

$$= 873.59 \angle \left(\frac{6\pi}{10} \right)$$

$$= 873.59 \left[\cos \left(\frac{6\pi}{10} \right) + j \sin \left(\frac{6\pi}{10} \right) \right]$$

$$= \underline{-269.96 + j 830.84}$$

$$P_2 = 873.59 \angle \left[\frac{\pi}{2} + \frac{\pi}{2N} + \frac{\pi}{N} \right]$$

$$= \underline{-706.75 + j 513.49}$$

$$P_3 = 873.59 \angle \pi = \underline{-873.59}$$

12.15

$$f_p = 10 \text{ kHz} \quad \frac{\omega_s}{\omega_p} = 1.5 \quad A_{\min} = 15 \text{ dB}$$

$$f_s = 15 \text{ kHz} \quad \omega_p \quad A_{\max} = 2 \text{ dB}$$

$$\epsilon^2 = 10^{A_{\max}/10} - 1 \Rightarrow \epsilon = 0.76478$$

CONT.

Manipulation Eq (12.15) we get:

$$N = \frac{\log \left[(10^{A_{\max}/10} - 1) / \epsilon^2 \right]}{2 \log (\omega_0 / \omega_p)} = 4.88$$

\therefore Use $N = 5$

Finding natural modes graphically :-

$$\text{radius} = \omega_p \left(\frac{1}{\epsilon} \right)^{1/N} \triangleq \omega_0$$

$$\omega_0 = 6.629 \times 10^4$$

$$\begin{aligned} P_1 &= \omega_0 \angle (\pi/2 + \pi/2N) = \omega_0 \angle (6\pi/10) \\ &= \omega_0 \left(\cos\left(\frac{6\pi}{10}\right) \pm j \sin\left(\frac{6\pi}{10}\right) \right) \\ &= \underline{\omega_0 (-0.309 \pm j0.951)} \end{aligned}$$

$$\begin{aligned} P_2 &= \omega_0 \left(\cos\frac{8\pi}{10} \pm j \sin\frac{8\pi}{10} \right) \\ &= \underline{\omega_0 (-0.809 \pm j0.588)} \end{aligned}$$

$$P_3 = \omega_0 (\cos\pi \pm j \sin\pi) = \underline{-\omega_0}$$

Given a natural mode $-\alpha \pm j\beta$, the following term results

$$\begin{aligned} &(s + \alpha + j\beta)(s + \alpha - j\beta) \\ &= s^2 + 2\alpha s + \alpha^2 + \beta^2 \\ &= \underline{s^2 + 2\text{Re}[P]s + |P|^2} \end{aligned}$$

Also, note that for a Butterworth, all natural modes have a magnitude of ω_0 .

$$P_1 \text{ yields: } s^2 + 0.618\omega_0 s + \omega_0^2$$

$$P_2 \text{ yields: } s^2 + 1.618\omega_0 s + \omega_0^2$$

$$P_3 \text{ yields: } s + \omega_0$$

$$\begin{aligned} \therefore T(s) &= \frac{k}{(s + \omega_0)(s^2 + 0.618\omega_0 s + \omega_0^2)} \\ &\times \frac{1}{s^2 + 1.618\omega_0 s + \omega_0^2} \end{aligned}$$

For unity dc gain

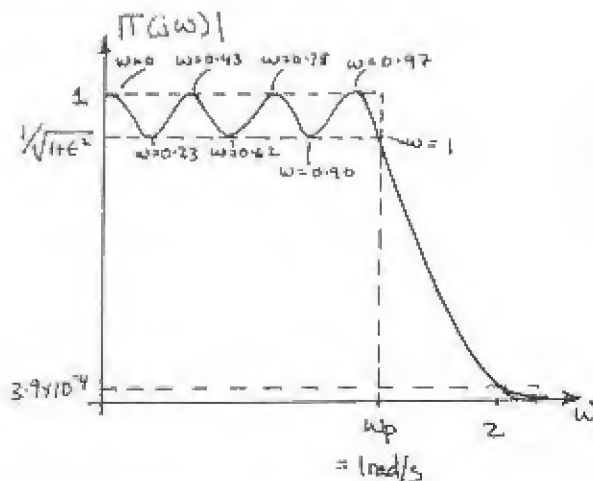
$$|T(j0)| = \frac{k}{\omega_0^5} = 1 \Rightarrow k = \omega_0^5$$

$$\begin{aligned} \therefore T(s) &= \frac{\omega_0^5}{(s + \omega_0)(s^2 + 0.618\omega_0 s + \omega_0^2)} \times \\ &\frac{1}{(s^2 + 1.618\omega_0 s + \omega_0^2)} \end{aligned}$$

For attenuation at 20 kHz use Eq (12.15) with $\frac{\omega_2}{\omega_p} = \frac{20}{10} = 2$

$$\begin{aligned} A(\omega_2) &= 10 \log \left[1 + \epsilon^2 \left(\frac{\omega_2}{\omega_p} \right)^{2N} \right] \\ &= \underline{27.8 \text{ dB}} \end{aligned}$$

12.16



$$\text{Given } A_{\max} = 1 \text{ dB} \Rightarrow \epsilon = 0.5088$$

CONT.

Using Eq 12.18

$$|T(j\omega)| = \left[1 + \epsilon^2 \cos^2 \left(N \cos^{-1} \left(\frac{\omega}{\omega_p} \right) \right) \right]^{-1/2}$$

for $\omega \leq \omega_p$

If $|T(j\omega)| = 1$

$$1 = 1 + \epsilon^2 \cos^2 \left(N \cos^{-1} \left(\frac{\omega}{\omega_p} \right) \right) \quad \omega_p = 1$$

$$N \cos^{-1} \left(\frac{\omega}{1} \right) = \cos^{-1}(0)$$

$$\cos^{-1}(\omega) = \frac{2i+1}{2N} \pi$$

ωs repeat after this value

$$\therefore \omega_i = \cos \left[\frac{2i+1}{2N} \pi \right] \quad i=0, 1, \dots, \frac{N-1}{2}$$

$$\omega_0 = 0.9749$$

$$\omega_1 = 0.7818$$

$$\omega_2 = 0.4339$$

$$\omega_3 = 0$$

ω values at which

$$|T|=1$$

note $\omega_4 = -0.4339$

$= -\omega_2$

If $|T| = 1/\sqrt{1+\epsilon^2}$, then

$$1/\sqrt{1+\epsilon^2} = \left[1 + \epsilon^2 \cos^2 \left(N \cos^{-1} \left(\frac{\omega}{\omega_p} \right) \right) \right]^{-1/2}$$

$$1 = \cos \left(N \cos^{-1} \left(\frac{\omega}{\omega_p} \right) \right)$$

$$N \cos^{-1}(\omega) = \cos^{-1}(0)$$

$$= i\pi \quad i=0, 1, 2, \dots$$

$$\omega_i = \cos \left[\frac{i\pi}{N} \right] \quad i=0, 1, 2, \dots, \frac{N}{2}$$

$$\omega_0 = 1.0$$

$$\omega_1 = 0.9010$$

$$\omega_2 = 0.6235$$

$$\omega_3 = 0.2252$$

ω values at which

$$|T| = (1+\epsilon^2)^{-1/2}$$

Note $\omega_4 = -0.2252$

$= -\omega_3$

To find $|T(j2)|$ use Eq (12.19)
since $\omega > \omega_p$

$$|T(j\omega)| = \left[1 + \epsilon^2 \cosh^2 \left(N \cosh^{-1} \left(\frac{\omega}{\omega_p} \right) \right) \right]^{-1/2}$$

$$= \left[1 + 0.5088^2 \cosh^2 (7 \cosh^{-1} 2) \right]^{-1/2}$$

$$= \underline{\underline{3.898 \times 10^{-4} \text{ V/V}}}$$

$$|T|_{dB} = \underline{\underline{-68.2 \text{ dB}}}$$

For roll-off consider

$$T(s) = \frac{k}{s^2 + b_1 s^4 + \dots + b_n}$$

for $\omega \gg \omega_p \quad |T(j\omega)| \approx \frac{k}{\omega^2}$

\therefore Roll-off is $\frac{1}{2}$ or $20 \log(1/2^2)$
per octave = $\underline{\underline{-42 \text{ dB/octave}}}$

12.17

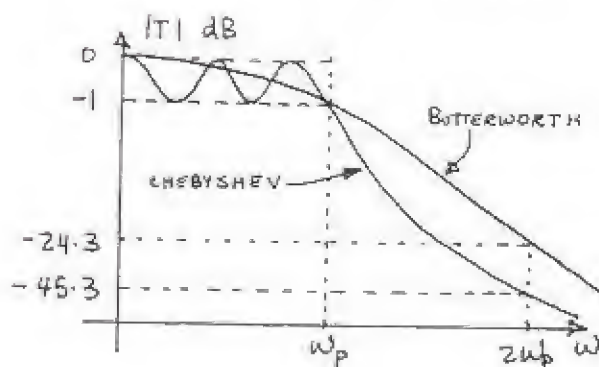
$$\omega_s/\omega_p = 2 \quad A_{max} = 1 \text{ dB} \Rightarrow \epsilon = \sqrt{10^{\frac{A_{max}}{10}} - 1} = 0.5088$$

$$|T_B| = \left[1 + \epsilon^2 \left(\frac{\omega_s}{\omega_p} \right)^{2N} \right]^{-1/2}$$

$$|T_C| = \left[1 + \epsilon^2 \cosh^2 \left(N \cosh^{-1} \left(\frac{\omega_s}{\omega_p} \right) \right) \right]^{-1/2}$$

$$|T_B| = 6.13 \times 10^{-2} \Rightarrow \underline{\underline{-24.3 \text{ dB}}}$$

$$|T_C| = 5.43 \times 10^{-3} \Rightarrow \underline{\underline{-45.3 \text{ dB}}}$$



12.18

$$f_p = 3.4 \text{ kHz} \quad A_{\max} = 1 \text{ dB} \Rightarrow \epsilon = 0.5088$$

$$f_s = 4 \text{ kHz} \quad A_{\min} = 35 \text{ dB}$$

$$\omega_s/\omega_p = 1.176$$

Using Eq (12.22) :

$$A(\omega_s) = 10 \log \left[1 + \epsilon^2 \cosh^2 \left(N \cosh^{-1} \left(\frac{\omega_s}{\omega_p} \right) \right) \right]$$

trying different values for N

N	A(ω _s)	} ∴ Use <u>N=10</u>
8	28.8 dB	
9	33.9 dB	
10	38.98 dB	

$$\text{Excess attenuation} = 39 - 35 = \underline{4 \text{ dB}}$$

Poles are given by:

$$P_k = -\omega_p \sin \left(\frac{2k-1}{N} \cdot \frac{\pi}{2} \right) \sinh \left(\frac{1}{N} \sinh^{-1} \left(\frac{1}{\epsilon} \right) \right) + j \omega_p \cos \left(\frac{2k-1}{N} \cdot \frac{\pi}{2} \right) \cosh \left(\frac{1}{N} \sinh^{-1} \left(\frac{1}{\epsilon} \right) \right)$$

for k = 1, 2, ..., N.

Since $\epsilon = 0.5088$ and $N = 10$

$$\sinh \left(\frac{1}{N} \sinh^{-1} \left(\frac{1}{\epsilon} \right) \right) = 0.1433$$

$$\cosh \left(\frac{1}{N} \sinh^{-1} \left(\frac{1}{\epsilon} \right) \right) = 1.010$$

$$\therefore P_1 = \omega_p \left[-0.1433 \sin \left(\frac{\pi}{20} \right) + j 1.010 \cos \left(\frac{\pi}{20} \right) \right] = \omega_p (-0.0224 + j 0.9978)$$

$$P_2 = \omega_p (-0.0650 + j 0.900)$$

$$P_3 = \omega_p (-0.1013 + j 0.7143)$$

$$P_4 = \omega_p (-0.1277 + j 0.4586)$$

$$P_5 = \omega_p (-0.1415 + j 0.1580)$$

Now it should be realized that the remaining poles are complex conjugates of the above.

Pole-pair P_1 & P_1^* give a factor:

$$s^2 + 2(0.0224)\omega_p s + \omega_p^2(0.0224^2 + 0.9978^2) = s^2 + 0.0448\omega_p s + 1.023\omega_p^2$$

i.e. this factor is from $(s - P_1)(s - P_1^*)$

$$P_2 \text{ yields: } s^2 + 0.130\omega_p s + 0.902\omega_p^2$$

$$P_3 \text{ yields: } s^2 + 0.203\omega_p s + 0.721\omega_p^2$$

$$P_4 \text{ yields: } s^2 + 0.265\omega_p s + 0.476\omega_p^2$$

$$P_5 \text{ yields: } s^2 + 0.283\omega_p s + 0.212\omega_p^2$$

Now $T(s)$ is given by

$$T(s) = \frac{k \omega_p^{10}}{\epsilon 2^9 (s - P_1)(s - P_1^*) \dots (s - P_5)(s - P_5^*)}$$

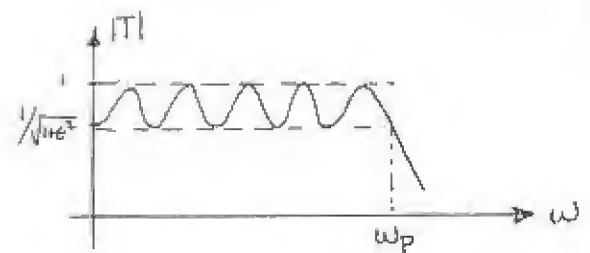
where the second order terms of the denominator are given above.

k is the dc gain

∴ we want the dc gain to be

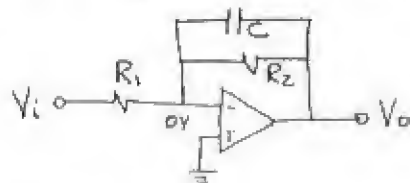
$$k = \frac{1}{1 + \epsilon^2} = \underline{0.8913}$$

$$\omega_p = \underline{2\pi \times 3400}$$



12.19

$$f_0 = 10 \text{ kHz} \quad \text{DC gain} = 10 \quad R_{in} = 10 \text{ k}\Omega$$



$$R_{in} = R_1 = 10 \text{ k}\Omega$$

$$\text{DC gain} = -R_2/R_1 = -10$$

$$R_2 = 10R_1 = 100 \text{ k}\Omega$$

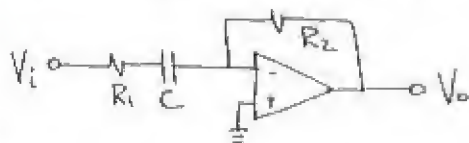
$$R_2 C = 1/\omega_0$$

$$C = \frac{1}{\omega_0 R_2} = \frac{1}{2\pi \cdot 10^4 \times 100 \times 10^3}$$

$$= 0.159 \text{ nF}$$

12.20

$$f_0 = 100 \text{ kHz} \quad R_i(\infty) = 100 \text{ k}\Omega \quad |T(\infty)| = 1$$



$$R_i(\infty) = R_1 = 100 \text{ k}\Omega$$

$$|T(\infty)| = R_2/R_1 = 1$$

$$R_2 = R_1 = 100 \text{ k}\Omega$$

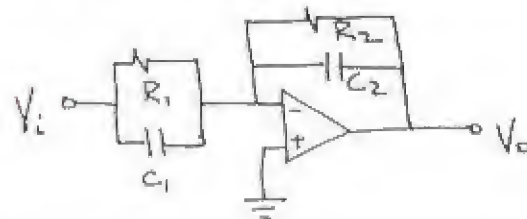
$$C R_1 = 1/\omega_0$$

$$C = \frac{1}{\omega_0 R_1} = \frac{1}{2\pi \cdot 100 \times 10^3 \times 100 \times 10^3}$$

$$= 15.9 \text{ nF}$$

12.21

Use general first-order circuit:



-Zero at 1 kHz; Pole at 100 kHz
 $|T(0)| = 1$; $R_i(0) = 1 \text{ k}\Omega$

$$\text{Thus: } R_i(\text{DC}) = R_1 = 1 \text{ k}\Omega$$

$$T(\text{DC}) = -R_2/R_1 = -1$$

$$R_2 = R_1 = 1 \text{ k}\Omega$$

For a pole at 100 kHz

$$C_2 R_2 = \frac{1}{\omega_0} \Rightarrow C_2 = \frac{1}{2\pi f_0 R_2}$$

$$= 1.59 \text{ nF}$$

For the circuit $T(s) = \frac{a_1 s + a_0}{s + \omega_0}$ Thus the zero at $-a_0/a_1 = -2\pi \cdot 10^3$

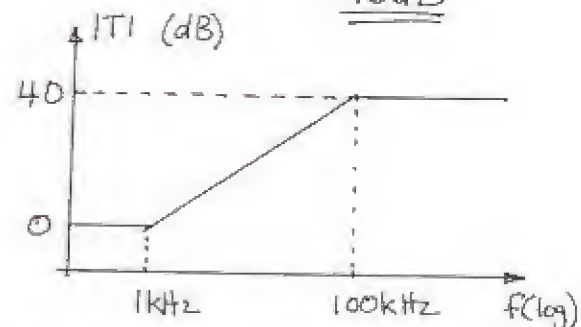
$$C_1 R_1 = a_1/a_0$$

$$C_1 = \frac{1}{2\pi \cdot 10^3 R_1}$$

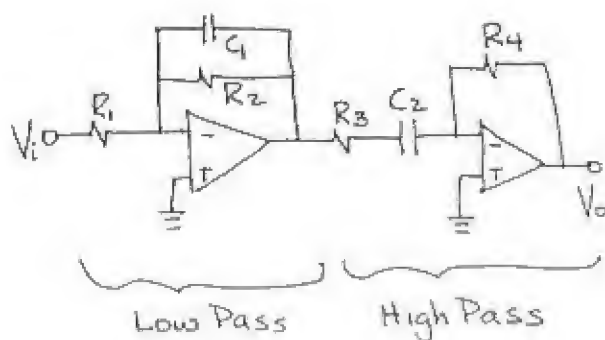
$$= 159 \text{ nF}$$

$$\text{High freq gain} = \frac{-C_1}{C_2} = \frac{-100}{1} = -100$$

$$= 40 \text{ dB}$$



12.22



$$\text{gain} = 10^{2/20} = 3.98 \approx 4$$

want $R_1 = R_2$ large
 $\therefore R_1 = \underline{100k\Omega}$

$$\text{Total gain} = A_{LP} A_{HP} = 4$$

$$A_{LP} = -R_2/R_1 \Rightarrow R_2 = -A_{LP} R_1 \text{ and } R_2 \leq 100k\Omega$$

$$\therefore \text{make } A_{LP} = -1 \quad A_{HP} = -4$$

$$R_2 = \underline{100k\Omega}$$

$$R_2 C_1 = \frac{1}{\omega_{LP}}$$

$$C_1 = \frac{1}{2\pi f_{0,LP} R_2} = \frac{1}{2\pi (10 \times 10^3) 100 \times 10^3}$$

$$= \underline{0.159nF}$$

$$A_{HP} = -R_4/R_3 = -4 \quad \left\{ \begin{array}{l} \text{make } R_4 = 100k\Omega \\ R_3 = 25k\Omega \end{array} \right.$$

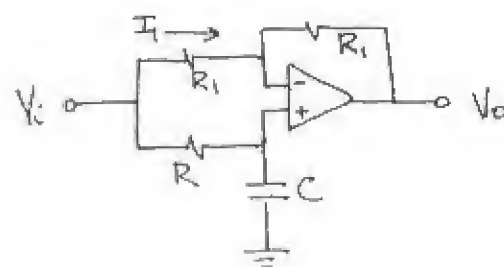
$$\text{now } R_3 C_2 = \frac{1}{\omega_{0,HP}}$$

$$C_2 = \frac{1}{2\pi f_{0,HP} R_3}$$

$$= \frac{1}{2\pi (100 \times 10^3) 25 \times 10^3}$$

$$= \underline{63.7nF}$$

12.23



At +ve terminal

$$V_+ = \frac{V_{sc}}{1/s\tau + R_1} V_i$$

$$= \frac{1}{1+s\tau} V_i \quad \tau = RC$$

$V_- = V_+$ due to virtual short between terminals.

$$\therefore I_1 = \left(V_i - \frac{1}{1+s\tau} V_i \right) \frac{1}{R_1}$$

$$V_o = V_- - I_1 R_1$$

$$= \frac{V_i}{1+s\tau} - \left(V_i - \frac{V_i}{1+s\tau} \right) \frac{R_1}{R_1}$$

$$\frac{V_o}{V_i} = \frac{1 - (1+s\tau) + 1}{1+s\tau} = \frac{1-s\tau}{1+s\tau}$$

$$= \frac{\omega_0 - s}{\omega_0 + s} \quad \omega_0 = \frac{1}{\tau}$$

$$= \underline{\underline{-\frac{s - \omega_0}{s + \omega_0} = T(s)}}$$

$$T(s) = -\frac{j\omega - \omega_0}{j\omega + \omega_0}$$

$$\phi(\omega) = 180^\circ + \tan^{-1}\left(\frac{\omega}{-\omega_0}\right) - \tan^{-1}\left(\frac{\omega}{\omega_0}\right)$$

$$= 360^\circ - 2\tan^{-1}\left(\frac{\omega}{\omega_0}\right) \quad \begin{array}{l} 0^\circ \tan^{-1}\left(\frac{\omega}{-\omega_0}\right) \\ = 180^\circ - \tan^{-1}\left(\frac{\omega}{\omega_0}\right) \end{array}$$

$$= -2\tan^{-1}(\omega/\omega_0)$$

Now this equation can be rearranged:

$$\frac{\omega}{\omega_0} = \tan(-\phi/2) \Leftarrow \omega_0 = \frac{1}{2} = \frac{1}{RC}$$

$$RC\omega = \tan(-\phi/2)$$

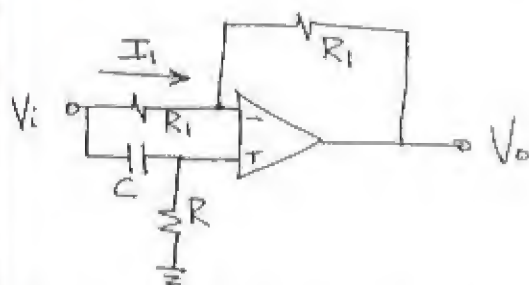
CONT.

$$\therefore R = \frac{\tan(-\phi/2)}{C\omega} = 10^4 \tan(\phi/2)$$

$$\phi = -30^\circ, -60^\circ, -90^\circ, -120^\circ, -150^\circ$$

$$R = 2.68 \text{ k}\Omega, 5.77 \text{ k}\Omega, 10 \text{ k}\Omega, 17.32 \text{ k}\Omega, 37.32 \text{ k}\Omega$$

12.24



$$V_+ = \frac{R}{R + 1/sC} V_i = \frac{s}{s + \omega_0} V_i$$

$$\text{where } \omega_0 = \frac{1}{RC}$$

$$I_1 = \frac{V_i - (s/s + \omega_0) V_i}{R_1}$$

$$V_o = \frac{s}{s + \omega_0} V_i - I_1 R_1$$

$$= \frac{s}{s + \omega_0} V_i - V_i \left(1 - \frac{s}{s + \omega_0}\right)$$

$$\frac{V_o}{V_i} = \frac{2s - s - \omega_0}{s + \omega_0} = \frac{s - \omega_0}{s + \omega_0}$$

Now:

$$\phi(\omega) = \tan^{-1}\left(\frac{\omega}{-\omega_0}\right) - \tan^{-1}\left(\frac{\omega}{\omega_0}\right)$$

$$= 180 - \tan^{-1}\left(\frac{\omega}{\omega_0}\right) - \tan^{-1}\left(\frac{\omega}{\omega_0}\right)$$

$$= 180 - 2 \tan^{-1}\left(\frac{\omega}{\omega_0}\right)$$

$$\text{Clearly } \phi(0) = 180^\circ \text{ \& } \phi(\omega \rightarrow \infty) = 0^\circ$$

12.25

$$\text{Low Pass } \omega_0 = 10^3 \text{ rad/s}$$

$$Q = 1$$

$$\text{DC gain} = 1$$

$$T(s) = \frac{a_0}{s^2 + s \frac{\omega_0}{Q} + \omega_0^2}$$

$$T(0) = a_0 / \omega_0^2 = 1$$

$$a_0 = \omega_0^2 = 10^6$$

$$\therefore T(s) = \frac{10^6}{s^2 + 10^3 s + 10^6}$$

$$\omega_{\max} = \omega_0 \sqrt{1 - 1/2Q^2}$$

$$= \frac{\omega_0}{\sqrt{2}}$$

$$= 0.707 \text{ rad/s}$$

$$|T_{\max}| = \frac{|a_0| Q}{\omega_0^2 \sqrt{1 - 1/4Q^2}} \ll a_0 = \omega_0^2$$

$$= \frac{1 \omega_0^2}{\omega_0^2 \sqrt{3/4}}$$

$$= 2/\sqrt{3}$$

$$= 1.15 \text{ V/V}$$

$$= 1.21 \text{ dB}$$

12.26

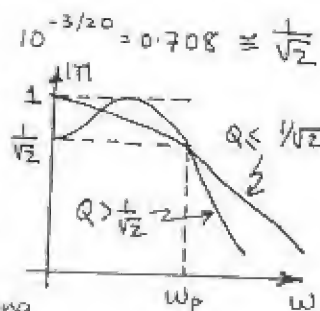
$$\omega_p = 1 \text{ rad/s}$$

$$A_{\max} = 3 \text{ dB}$$

There are many Q-values which may be used

$$Q \leq 1/\sqrt{2} \text{ - no peaking}$$

$$Q > 1/\sqrt{2} \text{ - peaking}$$



CONT.

Solution 1 $Q \leq 1/\sqrt{2}$

For $Q = 1/\sqrt{2}$ the response is maximally flat. Because this is desirable, use: $Q = \frac{1}{\sqrt{2}}$

$$T(s) = \frac{a_0}{s^2 + s\omega_0/\sqrt{2} + \omega_0^2}$$

$$|T(0)| = \frac{a_0}{\omega_0^2} = 1$$

$$\underline{a_0 = \omega_0^2}$$

$$|T(j\omega)|^2 = \frac{\omega_0^4}{(\omega_0^2 - \omega^2)^2 + 2\omega_0^2\omega^2} = \left(\frac{1}{\sqrt{2}}\right)^2$$

$$\omega_0 = 1 \text{ rad/s}$$

$$\therefore \underline{T_1(s) = \frac{1}{s^2 + \sqrt{2}s + 1}}$$

Solution 2 $Q > 1/\sqrt{2}$

From the figure: $|T(0)| = 1/\sqrt{2} = \frac{a_0}{\omega_0^2}$

$$\therefore \underline{a_0 = \omega_0^2/\sqrt{2}}$$

$$\text{Now } |T|_{\max} = \frac{|a_0|Q}{\omega_0^2\sqrt{1 - 1/4Q^2}} = 1$$

$$\frac{Q}{\sqrt{2}\sqrt{1 - 1/4Q^2}} = 1$$

$$Q = \sqrt{2}\sqrt{1 - 1/4Q^2}$$

$$\therefore Q^2 = 2\left(1 - \frac{1}{4Q^2}\right)$$

$$= 2 - \frac{1}{2Q^2}$$

$$Q^4 - 2Q^2 + \frac{1}{2} = 0$$

Solving for Q^2 gives:-

$$Q^2 = 1 \pm \sqrt{2}$$

ASIDE:

$$\therefore Q > 1/\sqrt{2}$$

$$Q^2 > 1/2$$

$$4Q^2 > 2$$

$$\frac{1}{4Q^2} < \frac{1}{2}$$

$$\therefore 1 - \frac{1}{4Q^2} > 1/2$$

$$\therefore \left|1 - \frac{1}{4Q^2}\right| = 1 - \frac{1}{4Q^2}$$

$$\Rightarrow Q = 0.5412 \text{ or } 1.3066$$

$$\therefore Q > \frac{1}{\sqrt{2}} \text{ use } \underline{Q = 1.3066}$$

Now at the passband edge

$$|T(j1)| = 1/\sqrt{2}$$

$$|T(j1)|^2 = \frac{(\omega_0^2/\sqrt{2})^2}{(\omega_0^2 - 1)^2 + \frac{\omega_0^4}{Q^2}} = \frac{1}{2}$$

$$\frac{\omega_0^4}{2} = \frac{1}{2} \left[\omega_0^4 - 2\omega_0^2 + 1 + \frac{\omega_0^4}{Q^2} \right]$$

$$\omega_0^2(2 - 1/Q^2) = 1$$

$$\underline{\omega_0 = 0.841}$$

$$\therefore T_2(s) = \frac{\omega_0^2/\sqrt{2}}{s^2 + \omega_0^2/Qs + \omega_0^2}$$

$$= \frac{0.5}{s^2 + 0.644s + 0.707}$$

If $\omega_s = 2$

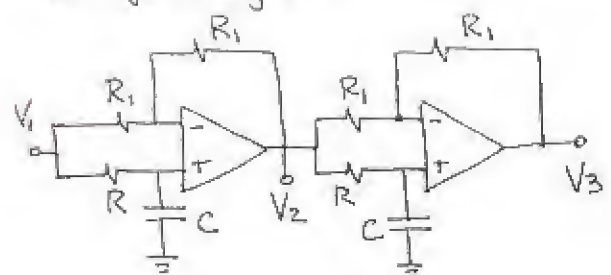
$$|T_1(j2)| = 0.242 \quad |T_2(j2)| = 0.1414$$

$$\therefore \underline{A_{min,1} = -12.3\text{dB}} \quad \underline{A_{min,2} = -17\text{dB}}$$

12.27

V_2 lags V_1 by 120°

V_3 lags V_2 by 120°



$$\omega = 2\pi 60 \quad \& \quad C = 1\mu\text{F}$$

$$T(s) = \frac{s - \omega_0}{s + \omega_0} \quad \omega_0 = \frac{1}{RC}$$

CONT.

$$\phi(\omega) = 180^\circ + \tan^{-1}\left(\frac{\omega}{-\omega_0}\right) - \tan^{-1}\left(\frac{\omega}{\omega_0}\right)$$

$$\text{Sub: } \tan\left(\frac{\omega}{-\omega_0}\right) = 180 - \tan^{-1}\left(\frac{\omega}{\omega_0}\right)$$

$$\Rightarrow \phi(\omega) = -2 \tan^{-1}(\omega/\omega_0)$$

$$\text{Now } \phi = -120^\circ \text{ at } \omega = 2\pi 60$$

$$-120 = -2 \tan^{-1}(\omega R C)$$

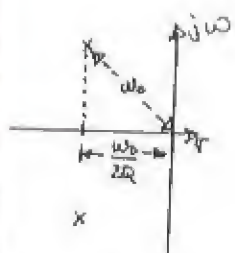
$$-60 = -\tan^{-1}(2\pi 60 \times R \times 10^{-6})$$

$$R = 4.59 \text{ k}\Omega$$

R_1 can be arbitrarily chosen

$$\text{use } R_1 = 10 \text{ k}\Omega$$

12.28



Natural modes:

$$-\frac{1}{2} \pm j \frac{\sqrt{3}}{2}$$

$$\omega_0 = \sqrt{\left(\frac{1}{2}\right)^2 + \left(\frac{\sqrt{3}}{2}\right)^2}$$

$$= 1.0$$

$$\frac{\omega_0}{2Q} = \frac{1}{2} \Rightarrow \frac{\omega_0}{Q} = 1$$

$$T(s) = \frac{a_2 s^2}{s^2 + s \frac{\omega_0}{Q} + \omega_0^2} = \frac{a_2 s^2}{s^2 + s + 1}$$

$$|T(j\infty)| = a_2 = 1$$

$$\therefore T(s) = \frac{s^2}{s^2 + s + 1}$$

12.29

For a 2nd-order bandpass

$$T(s) = \frac{a_1 s}{s^2 + s \frac{\omega_0}{Q} + \omega_0^2}$$

$$T(j\omega) = \frac{j \omega a_1}{(\omega_0^2 - \omega^2) + j \frac{\omega \omega_0}{Q}}$$

$$|T(j\omega)| = \frac{a_1 \omega}{\left[(\omega_0^2 - \omega^2)^2 + \frac{\omega^2 \omega_0^2}{Q^2} \right]^{1/2}}$$

Part (a):

$$|T(j\omega_1)| = |T(j\omega_2)|$$

$$\frac{a_1 \omega_1}{\sqrt{(\omega_0^2 - \omega_1^2)^2 + \left(\frac{\omega_1 \omega_0}{Q}\right)^2}} = \frac{a_1 \omega_2}{\sqrt{(\omega_0^2 - \omega_2^2)^2 + \left(\frac{\omega_2 \omega_0}{Q}\right)^2}}$$

$$\omega_1^2 \left[(\omega_0^2 - \omega_2^2)^2 + \left(\frac{\omega_2 \omega_0}{Q}\right)^2 \right] = \omega_2^2 \left[(\omega_0^2 - \omega_1^2)^2 + \left(\frac{\omega_1 \omega_0}{Q}\right)^2 \right]$$

$$\omega_1^2 (\omega_0^4 - 2\omega_0^2 \omega_2^2 + \omega_2^4) =$$

$$\omega_2^2 (\omega_0^4 - 2\omega_0^2 \omega_1^2 + \omega_1^4)$$

$$\omega_1^2 \omega_0^4 + \omega_1^2 \omega_2^4 = \omega_2^2 \omega_0^4 + \omega_2^2 \omega_1^4$$

$$\omega_0^4 (\omega_1^2 - \omega_2^2) = \omega_2^2 \omega_1^4 - \omega_1^2 \omega_2^4$$

$$\omega_0^4 (\omega_1^2 - \omega_2^2) = \omega_2^2 \omega_1^2 (\omega_1^2 - \omega_2^2)$$

$$\omega_0^4 = \omega_1^2 \omega_2^2$$

$$\underline{\underline{\omega_0^2 = \omega_1 \omega_2 \text{ Q.E.D.}}}$$

CONT.

For Fig. 12.4: $\omega_{p1} = 8100 \text{ rad/s}$
 $\omega_{p2} = 10000 \text{ rad/s}$
 $A_{\max} = 1 \text{ dB}$

$$\omega_0^2 = (8100)(10000)$$

$$\omega_0 = \underline{9000 \text{ rad/s}}$$

$$|T(j\omega_{p1})| = |T(j\omega_{p2})| = 10^{-1/20} \\ = \underline{0.8913}$$

$$|T(j\omega_0)| = \frac{\omega_0 a_1}{\sqrt{(\omega_0^2 - \omega_0^2)^2 + \left(\frac{\omega_0^2}{Q}\right)^2}} = 1 \\ \Rightarrow \frac{\omega_0 a_1}{\omega_0^2 / Q} = 1$$

$$\therefore \frac{Q a_1}{\omega_0} = 1 \Rightarrow a_1 = \frac{\omega_0}{Q}$$

$$|T(j\omega_{p1})|^2 = |T(j0.9\omega_0)|^2 = 0.8913^2$$

$$\frac{(\omega_0/Q)^2 (0.9\omega_0)^2}{(\omega_0^2 - (0.9\omega_0)^2)^2 + \left(\frac{0.9\omega_0}{Q}\right)^2} = 0.8913^2$$

$$\left(\frac{\omega_0}{Q} (0.9\omega_0)\right)^2 = 0.8913^2 \left[(\omega_0^2 - (0.9\omega_0)^2)^2 + \left(\frac{0.9\omega_0}{Q}\right)^2 \right]$$

$$\frac{0.81\omega_0^4}{Q^2} = 0.8913^2 \left[\omega_0^4 (1 - 0.81)^2 + \frac{0.81\omega_0^4}{Q^2} \right]$$

$$\frac{0.81\omega_0^4}{Q^2} (1 - 0.8913^2) = 0.8913^2 \omega_0^4 \times (1 - 0.81)^2$$

sub $\omega_0 = 9000$ gives

$$\underline{Q = 2.41}$$

$$\text{Now } a_1 = \frac{\omega_0}{Q} = 0.415 \omega_0$$

$$\therefore T(s) = \frac{0.415 \omega_0 s}{s^2 + 0.415 \omega_0 s + \omega_0^2}$$

$$\text{If } \omega_{s1} = 3000 \text{ rad/s}$$

$$|T(j3000)| = \frac{0.415 \omega_0 (3000)}{\sqrt{(\omega_0^2 - 3000^2)^2 + (\omega_0 3000 \times 0.415)^2}}$$

$$= 0.1537$$

$$\therefore A_{\min} = -20 \log(0.1537) \\ = \underline{16.3 \text{ dB}}$$

Now ω_{s1} and ω_{s2} are geometrically symmetrical about ω_0 :

$$\omega_{s1} \omega_{s2} = \omega_0^2$$

$$\omega_{s2} = \frac{9000^2}{3000}$$

$$= \underline{27000 \text{ rad/s}}$$

12.30

From exercise 12.15

$$Q = \frac{\omega_0}{BW \sqrt{10^{A/10} - 1}} \quad \begin{cases} \omega_0 = 2\pi(60) \\ BW = 2\pi(6) \\ A = 20 \text{ dB} \end{cases} \\ = \underline{1.005}$$

$$T(s) = a_2 \frac{s^2 + \omega_0^2}{s^2 + s \frac{\omega_0}{Q} + \omega_0^2}$$

$$|T(0)| = \frac{a_2 \omega_0^2}{\omega_0^2} = 1 \leftarrow \text{DC Gain}$$

CONT.

$$\underline{a_2 = 1}$$

$$T(s) = \frac{s^2 + (2\pi 60)^2}{s^2 + s \frac{2\pi 60}{1.005} + (2\pi 60)^2}$$

$$\underline{T(s) = \frac{s + 1.421 \times 10^5}{s^2 + 375.1s + 1.421 \times 10^5}}$$

12.32

$$T(s) = \frac{s^2 - s \omega_0/Q' + \omega_0^2}{s^2 + s \omega_0/Q_0 + \omega_0^2} a_2$$

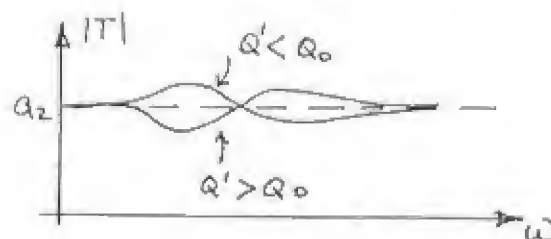
$$\text{Zero } Q < \text{ Pole } Q \Rightarrow Q' < Q_0$$

At $\omega = \omega_0$:

$$|T| = \frac{a_2 \omega_0^2/Q'}{\omega_0^2/Q_0} = \frac{a_2 Q_0}{Q'} > a_2$$

If $Q' > Q_0$

$$|T(j\omega_0)| = \frac{a_2 Q_0}{Q'} < a_2$$



12.31

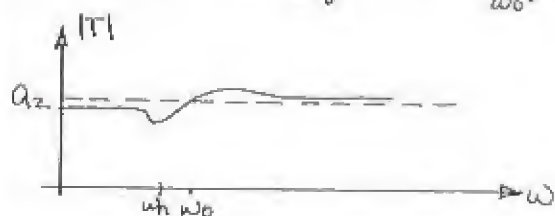
For All Pass:

$$T(s) = a_2 \frac{s^2 - s \omega_0/Q + \omega_0^2}{s^2 + s \omega_0/Q + \omega_0^2}$$

If zero frequency < pole frequency

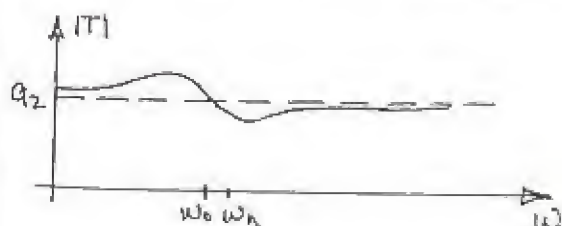
$$T(s) = a_2 \frac{s^2 - s \omega_n/Q + \omega_n^2}{s^2 + s \omega_0/Q + \omega_0^2} \quad \omega_n < \omega_0$$

$$\text{At DC: } |T| = a_2 \frac{\omega_n^2}{\omega_0^2} \quad \text{where } \frac{\omega_n^2}{\omega_0^2} < 1$$



If zero frequency > pole frequency
then $\omega_n > \omega_0$

$$\text{At DC: } |T| = a_2 \omega_n^2/\omega_0^2 \quad \text{where } \frac{\omega_n^2}{\omega_0^2} > 1$$



12.33

$$\omega_0 = 10^4 \text{ rad/s}, \quad Q = 2, \quad R = 10 \text{ k}\Omega$$

$$\omega_0 = \frac{1}{\sqrt{LC}} \Rightarrow \omega_0^2 = \frac{1}{LC} \Leftrightarrow L = \frac{R^2 C}{Q^2} = \frac{Q^2}{R^2 C^2}$$

$$C = \frac{Q}{R \omega_0} = \underline{\underline{20 \text{ nF}}}$$

$$L = \frac{1}{C \omega_0^2} = \underline{\underline{500 \text{ mH}}}$$

12.34

$$\omega_0 = 1/\sqrt{LC}$$

If $L' = 1.01L$

$$\omega_0' = (1.01LC)^{-1/2}$$

$$= 0.9950 \frac{1}{\sqrt{LC}}$$

$$= 0.9950 \omega_0$$

$$\therefore \Delta\omega_0 = -0.5\%$$

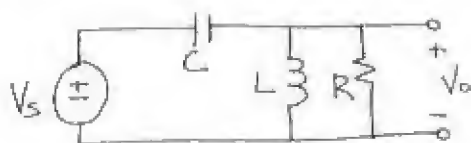
If $C' = 1.01C$

$$\omega_0' = 0.9950 \omega_0$$

$$\Delta\omega_0' = -0.5\%$$

Changing R has no effect on ω_0

12.35



Use voltage divider rule:

$$V_o = \frac{Z_{RL}}{Z_{RL} + Z_C} V_s$$

$$\frac{V_o}{V_s} = \frac{\left(\frac{1}{R} + \frac{1}{sL}\right)^{-1}}{\left(\frac{1}{R} + \frac{1}{sL}\right)^{-1} + \frac{1}{sC}}$$

$$= \frac{sC}{\left(\frac{1}{sC} + \frac{1}{R}\right) + sC}$$

$$\therefore T(s) = \frac{V_o(s)}{V_s(s)} = \frac{s^2}{s^2 + s/RC + 1/LC}$$

12.36

Low Pass: $\omega_0 = 10^5$, $C = 0.1 \mu F$
 $Q = 1/\sqrt{2}$

$$Q = \omega_0 CR$$

$$R = \frac{Q}{\omega_0 C}$$

$$= \frac{1}{\sqrt{2} \times 10^5 \times 0.1 \times 10^{-6}}$$

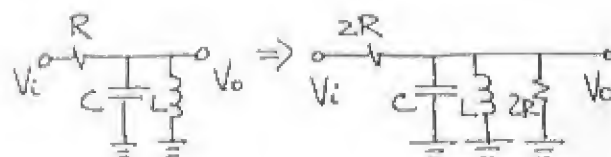
$$= \underline{\underline{70.7 \Omega}}$$

$$\omega_0 = 1/\sqrt{LC}$$

$$L = \frac{1}{\omega_0^2 C}$$

$$= \underline{\underline{1mH}}$$

12.37



$$\omega_0 = \frac{1}{\sqrt{LC}}$$

$$Q = \omega_0 CR$$

$$A_{mid} = 1$$

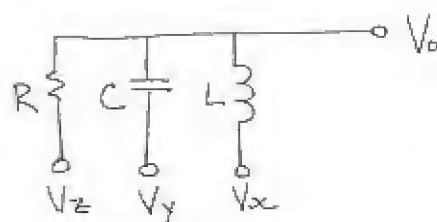
$$\omega_0 = 1/\sqrt{LC}$$

$$Q = \omega_0 C (2R \parallel 2R)$$

$$= \omega_0 CR$$

$$A_{mid} = \frac{2R}{2R + 2R} = 1/2$$

12.38



$$\left. \frac{V_o}{V_z} \right|_{V_y = V_x = 0} = T_{sp}(s)$$

$$\left. \frac{V_o}{V_y} \right|_{V_z = V_x = 0} = T_{hp}(s)$$

CONT.

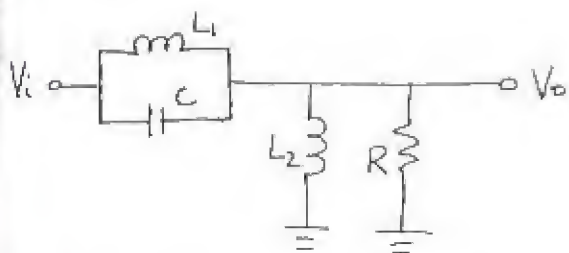
$$\left. \frac{V_o}{V_x} \right|_{V_y=V_z=0} = T_{LP}(s)$$

Using superposition

$$\begin{aligned} V_o &= \frac{V_o}{V_x} V_x + \frac{V_o}{V_y} V_y + \frac{V_o}{V_z} V_z \\ &= T_{LP} V_x + T_{HP} V_y + T_{BP} V_z \\ &= \frac{\frac{1}{LC} V_x + s^2 V_y + \frac{s}{RC} V_z}{s^2 + s/RC + 1/LC} \end{aligned}$$

$$\begin{aligned} \therefore V_o &= V_x \frac{1/LC}{s^2 + s/RC + 1/LC} + \\ &V_y \frac{s^2}{s^2 + s/RC + 1/LC} + \\ &V_z \frac{s/RC}{s^2 + s/RC + 1/LC} \end{aligned}$$

12.39



From Eq 12.46

$$T(s) = \frac{s^2 + 1/L_1 C}{s^2 + s(1/RC) + \frac{1}{(L_1 \parallel L_2)C}}$$

$$\text{Required notch } \omega_n^2 = \frac{1}{L_1 C} = (0.9\omega_0)^2$$

but:

$$\omega_0^2 = \frac{1}{(L_1 \parallel L_2)C} \quad \text{where } L_1 \parallel L_2 = \frac{1}{\frac{1}{L_1} + \frac{1}{L_2}}$$

$$= \frac{L_1 L_2}{L_1 + L_2} \quad = \frac{L_1 L_2}{4 + L_2}$$

$$= \frac{L_1 + L_2}{L_2} (0.9\omega_0)^2$$

$$1 = \left(\frac{L_1}{L_2} + 1 \right) 0.9^2$$

$$\therefore L_1/L_2 = \frac{1}{0.9^2} - 1 = \underline{\underline{0.2346}}$$

For $\omega \ll \omega_0$:-

$$|T| \cong \frac{1/L_1 C}{1/(L_1 \parallel L_2)C} = \frac{L_2}{L_1 + L_2}$$

i.e. inductors dominate!

For $\omega \gg \omega_0$ L_1 & L_2 are 'open'
C is shorted

$$|T| \cong 1$$

12.40

$$L = C_4 R_1 R_3 R_5 / R_2$$

$$\text{Choose } \underline{\underline{R_1 = R_2 = R_3 = R_5 = 10k\Omega}}$$

$$\therefore L = C_4 \times 10^8$$

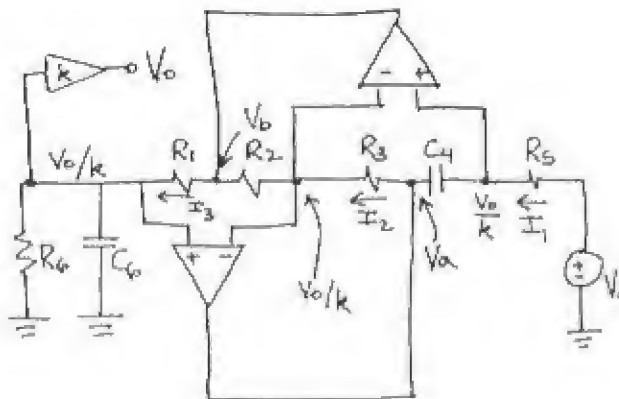
For:

$$L = 10H = C_4 \times 10^8 \Rightarrow \underline{\underline{C_4 = 100nF}}$$

$$L = 1H \Rightarrow \underline{\underline{C_4 = 10nF}}$$

$$L = 0.1H \Rightarrow \underline{\underline{C_4 = 1nF}}$$

12.41



Because of the virtual short at opamp input terminals, the voltages are V_0/k

$$I_1 = \frac{V_i - V_0/k}{R_5}$$

$$\begin{aligned} V_a &= V_0/k - I_1 / sC_4 \\ &= V_0/k - \frac{V_i - V_0/k}{sC_4 R_5} \\ &= \frac{V_0(sC_4 R_5 + 1) - kV_i}{sC_4 R_5 k} \end{aligned}$$

$$\begin{aligned} I_2 &= \frac{V_a - V_0/k}{R_3} \\ &= -\frac{V_i}{sC_4 R_3 R_5} + \frac{V_0/k}{sC_4 R_3 R_5} \end{aligned}$$

$$\begin{aligned} V_b &= \frac{V_0}{k} - I_2 R_2 \\ &= \frac{V_0}{k} - \frac{V_0/k - V_i}{sC_4 R_3 R_5 / R_2} \end{aligned}$$

$$I_3 = \frac{V_b - V_0/k}{R_1} = \frac{V_i - V_0/k}{sC_4 R_1 R_3 R_5 / R_2}$$

Now, I_3 flows only into $R_6 \parallel C_6$ since for ideal opamps, $R_{in} = \infty$!

$$\therefore \frac{V_0}{k} = I_3 \left(R_6 \parallel \frac{1}{sC_6} \right)$$

$$\text{Let } L \triangleq \frac{R_1 R_3 R_5 C_4}{R_2}$$

$$\text{So: } I_3 = \frac{V_i - V_0/k}{sL}$$

$$V_0/k = I_3 \left(R_6 \parallel \frac{1}{sC_6} \right)$$

$$\begin{aligned} \frac{V_0}{k} &= \frac{V_i - V_0/k}{sL} \cdot \frac{1}{1/R_6 + sC_6} \\ &= \frac{V_i - V_0/k}{sL/R_6 + s^2 LC_6} \end{aligned}$$

$$V_0/k \left(1 + sL/R_6 + s^2 LC_6 \right) = V_i$$

$$\frac{V_0}{V_i} = \frac{k/LC_6}{s^2 + \frac{s}{R_6 C_6} + \frac{1}{LC_6}}$$

$$\text{Recall } L = R_1 R_3 R_5 C_4 / R_2$$

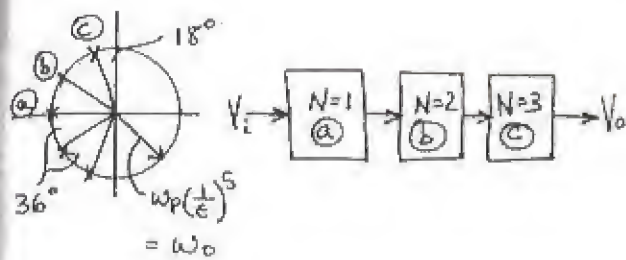
$$\therefore \frac{V_0}{V_i} = \frac{\frac{kR_2}{C_4 R_1 R_3 R_5}}{s^2 + \frac{s}{R_6 C_6} + \frac{R_2}{C_6 C_4 R_1 R_3 R_5}}$$

12.42

$$A_{\max} = 10 \log(1 + \epsilon^2) = 3 \text{ dB}$$

$$\therefore \epsilon = 0.998 \approx 1$$

$$\omega_0 = \omega_p = 10^4$$



For circuit (a) use fig 12.13(a)

$$\text{DC Gain} = 1 = R_2/R_1 \Rightarrow R_1 = R_2 = 10 \text{ k}\Omega$$

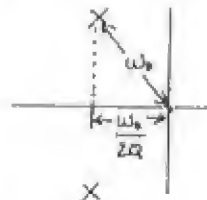
$$CR_2 = 1/\omega_0 \Rightarrow C = 1/R_2 \omega_0 = \frac{1}{10^4 \cdot 10^4} = 10 \text{ nF}$$

For circuit (b) use Fig. 12.22(a)

$$\omega_0 = 10^4 \text{ rad/s}$$

$$\frac{\omega_0}{2Q} = \omega_0 \cos 36^\circ$$

$$Q = \frac{1}{2 \cos 36^\circ} = 0.618$$



From Table 12.1

$$T(s) = \frac{k R_2}{C_4 C_6 R_1 R_3 R_5} \frac{R_2}{s^2 + s/C_6 R_6 + \frac{R_2}{C_4 C_6 R_1 R_3 R_5}}$$

$$\omega_0^2 = \frac{R_2}{C_4 C_6 R_1 R_3 R_5} \quad \text{Let } R_1 = R_3 = R_5 = R_2 = R$$

$$C_4 = C_6 = C$$

$$\omega_0^2 = \frac{1}{R^2 C^2} \quad \text{USE } C_4 = C_6 = 100 \text{ nF}$$

$$\therefore R = \frac{1}{\omega_0 C} \Rightarrow R_1 = R_3 = R_5 = R_2 = 1 \text{ k}\Omega$$

Now using:

$$\frac{\omega_0}{Q} = \frac{1}{C_6 R_6} \quad \& \quad Q = 0.618$$

$$R_6 = \frac{Q}{C_6 \omega_0} = 618 \Omega$$

For circuit (c) use Fig 12.22 (a)

$\omega_0 = 10^4$ which is the same as for circuit (b).

$$\therefore C_4 = C_6 = 100 \text{ nF}$$

$$R_1 = R_2 = R_3 = R_5 = 1 \text{ k}\Omega$$

$$\text{Now: } Q = \frac{1}{2 \cos 72^\circ} = 1.618$$

$$R_6 = Q/\omega_0 C_6 = 1.618 \text{ k}\Omega$$

12.43

$$f_0 = 4 \text{ kHz} \quad f_N = 5 \text{ kHz} \quad Q = 10$$

now $C_4 = 10 \text{ nF}$ and $K = 1 \equiv \text{dc gain}$

$$\omega_0 = [C_4 (C_{61} + C_{62}) R_1 R_3 R_5 / R_2]^{-1/2}$$

$$C_{61} + C_{62} = C_6$$

Choose $C_4 = C_6 = 10 \text{ nF}$ &

$$R_1 = R_3 = R_5 = R_2 = R$$

$$\therefore \omega_0 = (C_4 C_6 R^2)^{-1/2}$$

$$R = \frac{1}{\omega_0 C_4}$$

$$\Rightarrow R_1 = R_3 = R_5 = R_2 = 3.979 \text{ k}\Omega$$

$$\omega_N = (C_4 C_{61} R^2)^{-1/2}$$

$$C_{61} = \frac{1}{\omega_N^2 R^2 C_4} \Rightarrow C_{61} = 6.4 \text{ nF}$$

$$\& \quad C_{62} = 3.6 \text{ nF}$$

$$Q = R_6 \sqrt{\frac{C_{61} + C_{62}}{C_4}} \cdot \frac{R_2}{R_1 R_3 R_5}$$

$$= R_6 \sqrt{\frac{1}{R_1^2}} = R_6/R_1 \Rightarrow R_6 = 39.79 \text{ k}\Omega$$

12.44

From Fig. 12.16 (g) $\phi = 180^\circ$ at f_0 !

∴ Use $f_0 = 1 \text{ kHz}$ $Q = 1$

$$\omega_0^2 = \frac{R_2}{C_4 C_6 R_1 R_3 R_5} \quad \text{LET } C = C_4 = C_6 = 1 \text{ nF}$$

$$R_1 = R_3 = R_5 = R_2 = R$$

$$= \frac{1}{C^2 R^2}$$

$$R = \frac{1}{\omega_0^2 C} = \frac{159.16 \text{ k}\Omega}{1} = R_1 = R_3 = R_5 = R_2$$

$$\frac{\omega_0}{Q} = \frac{1}{R_6 C_6} \Rightarrow R_6 = \frac{Q}{C_6 \omega_0}$$

$$= \frac{1}{10^{-9} 2\pi 10^3}$$

$$\therefore R_6 = 159.16 \text{ k}\Omega$$

$$V_a = V_2 - I_1 R_1$$

$$= V_2 (1 + s C_6 R_1)$$

$$I_2 = (V_a - V_2) \frac{1}{R_2}$$

$$= \frac{s C_6 R_1}{R_2} V_2$$

$$V_b = V_2 - I_2 R_3$$

$$= V_2 - \frac{s C_6 R_1 R_3}{R_2} V_2$$

$$I_3 = (V_b - V_2) s C_4$$

$$= - \frac{s^2 C_4 C_6 R_1 R_3}{R_2} V_2$$

Now the voltage source sees an input impedance given by:

$$Z_{in} = -V_2 / I_3 = \frac{R_2}{s^2 C_4 C_6 R_1 R_3}$$

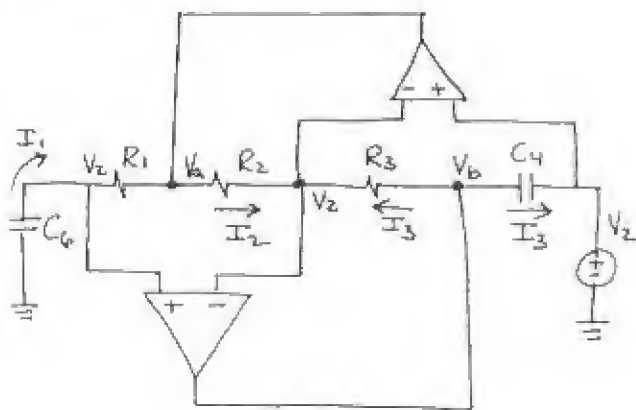
As required.

$$\text{for } s = j\omega \Rightarrow s^2 = -\omega^2$$

$$Z_{in}(j\omega) = \frac{-R_2}{C_4 C_6 R_1 R_3} \cdot \frac{1}{\omega^2}$$

$$= -R(\omega) \quad \text{ie. A PURE NEGATIVE RESISTANCE!}$$

12.45



Because of virtual short at opamp input terminals all nodes are at V_2 !

$$I_1 = -s C_6 V_2$$

Since no current goes into the opamp input terminals we have:

12.46

For LPN: See Table 12.1 & Fig. 12.22 (e)

$$T(s) = k \frac{C_{61}}{C_{61} + C_{62}} \cdot \frac{s^2 + \frac{R_2}{C_4 C_6 R_1 R_3 R_5}}{s^2 + s / C_6 R_6 + \frac{R_2}{C_4 (C_{61} + C_{62}) R_1 R_3 R_5}}$$

At DC $\rightarrow s = 0$

$$T(0) = k \frac{C_{61}}{C_{61} + C_{62}} \cdot \frac{R_2 / C_4 C_6 R_1 R_3 R_5}{R_2 / C_4 (C_{61} + C_{62}) R_1 R_3 R_5}$$

CONT.

$$\Rightarrow T(0) = k \triangleq \text{DC Gain!}$$

Note that $C_{01} + C_{02}$ is the total capacitance across R_0

$$\therefore C_0 = C_{01} + C_{02}$$

$$\frac{\omega_n^2}{\omega_0^2} = \frac{R_2 / C_4 C_{01} R_1 R_3 R_5}{R_2 / C_4 (C_{01} + C_{02}) R_1 R_3 R_5}$$

$$= \frac{C_{01}}{C_{01} + C_{02}}$$

$$\frac{\omega_n^2}{\omega_0^2} = \frac{C_{01}}{C_0}$$

$$\therefore C_{01} = C_0 \left(\frac{\omega_n}{\omega_0} \right)^2 = C \left(\frac{\omega_n}{\omega_0} \right)^2$$

Clearly from $T(s)$ above:

$$\omega_n^2 = R_2 / C_4 C_{01} R_1 R_3 R_5$$

$$\Rightarrow \omega_n = \sqrt{\frac{R_2}{C_4 C_{01} R_1 R_3 R_5}}$$

$$\omega_0^2 = R_2 / C_4 C_0 R_1 R_3 R_5$$

$$\Rightarrow \omega_0 = \sqrt{\frac{R_2}{C_4 (C_{01} + C_{02}) R_1 R_3 R_5}}$$

$$\omega_0 = \sqrt{\frac{R_2}{C_4 C_0 R_1 R_3} \left(\frac{1}{R_{S1}} + \frac{1}{R_{S2}} \right)}$$

At high frequencies $s \rightarrow \infty$

$$T(\infty) = k \triangleq \text{high freq gain.}$$

Observe that the equivalent resistance at the +ve terminal of A_1 is:

$$\frac{1}{R_S} = \frac{1}{R_{S1}} + \frac{1}{R_{S2}} \quad \text{AND}$$

for the resonator (table 12.1)

$$R_S = 1/\omega_0 C \Rightarrow \frac{1}{R_S} = \omega_0 C$$

$$\frac{\omega_0^2}{\omega_n^2} = \frac{R_2 / C_4 C_0 R_1 R_3 R_5}{R_2 / C_4 C_{01} R_1 R_3 R_5} \Rightarrow R_{S1} = R_S \frac{\omega_0^2}{\omega_n^2}$$

$$\text{Now } \frac{1}{R_S} = \frac{1}{R_S \frac{\omega_0^2}{\omega_n^2}} + \frac{1}{R_{S2}}$$

$$\frac{1}{R_{S2}} = \frac{1}{R_S} \left[1 - \frac{\omega_n^2}{\omega_0^2} \right]$$

$$R_{S2} = \frac{R_S}{1 - \omega_n^2 / \omega_0^2}$$

12.47

For HPN: See Table 12.1 & Fig 11.22(f)

$$T(s) = k \frac{s^2 + \left(\frac{R_2}{C_4 C_0 R_1 R_3 R_{S1}} \right)}{s^2 + \frac{s}{C_4 R_4} + \left(\frac{R_2}{C_4 C_0 R_1 R_3} \right) \left(\frac{1}{R_{S1}} + \frac{1}{R_{S2}} \right)}$$

$$\text{clearly: } \omega_n = \sqrt{\frac{R_2}{C_4 C_0 R_1 R_3 R_{S1}}}$$

12.48

$$T(s) = \frac{0.4508 (s^2 + 1.6996)}{(s + 0.7294) (s^2 + 0.2786s + 1.0504)}$$

PART (a) Replace s with s/ω_p

$$T(s) = \frac{0.4508 \left(\frac{s^2}{\omega_p^2} + 1.6996 \right)}{\left(\frac{s}{\omega_p} + 0.7294 \right) \left(\frac{s^2}{\omega_p^2} + \frac{0.2786s}{\omega_p} + 1.0504 \right)}$$

CONT.

$$T(s) = \frac{0.4508 \omega_p (s^2 + 1.6996 \omega_p^2)}{(s + 0.7294 \omega_p)(s^2 + 0.2786 \omega_p s + 1.0504 \omega_p^2)}$$

$$\text{so } \omega_p = 10^4 \text{ rad/s}$$

$$T(s) = \frac{4508 (s^2 + 1.6996 \times 10^8)}{(s + 7294)(s^2 + 2786s + 1.0504 \times 10^8)}$$

Part (b)

First decompose $T(s)$ into 1st- and 2nd-order sections with unity DC gain!

$$T_1(s) = \frac{k_1}{s + 7294} \quad T_1(0) = \frac{k_1}{7294} = 1$$

$$\Rightarrow k_1 = 7294$$

$$\text{Now } k_1 k_2 = 4508 \Rightarrow k_2 = 0.6180$$

$$\therefore T_2(s) = \frac{0.6180 (s^2 + 1.6996 \times 10^8)}{s^2 + 2786s + 1.0504 \times 10^8}$$

As a check:

$$T_2(0) = \frac{0.6180 (1.6996 \times 10^8)}{1.0504 \times 10^8} = 1.000$$

As EXPECTED!

$$\therefore T(s) = T_1(s) \cdot T_2(s)$$

For first-order section use Fig 12.13(a)

$$\omega_0 = 7294 \text{ rad/s} \quad \text{DC Gain} = 1$$

$$\text{Let } C = 10 \text{ nF}$$

$$R_1 = R_2 = \frac{1}{\omega_0 C} \Rightarrow R_1 = R_2 = 13.71 \text{ k}\Omega$$

For second-order section

$$\omega_n^2 = 1.6996 \times 10^8 \Rightarrow \omega_n = 13.037 \times 10^3$$

$$\omega_0^2 = 1.0504 \times 10^8 \Rightarrow \omega_0 = 10.249 \times 10^3$$

$$\frac{\omega_0}{Q} = 2786 \Rightarrow Q = 3.6787$$

For LPN use table 12.1 and Fig 12.22(e)

Make $R_1 = R_2 = R_3 = R_5 = R$ and

$$C = C_4 = C_6 = 10 \text{ nF}$$

$$R = \frac{1}{\omega_0 C} = 9.757 \text{ k}\Omega = R_1 = R_2 = R_3 = R_5$$

$$\omega_n^2 = \frac{1}{C R^2 C_{G1}} \Rightarrow C_{G1} = 6.18 \text{ nF}$$

$$C_{G2} = C - C_{G1} = 3.82 \text{ nF}$$

$$Q = R_6 \sqrt{\frac{C_6}{C_4} \frac{R_2}{R_1 R_3 R_5}} = \frac{R_6}{\sqrt{R^2}} = \frac{R_6}{R}$$

$$\therefore R_6 = RQ = (9.757 \times 10^3)(3.6787) = 35.89 \text{ k}\Omega$$

12.49

$$f_0 = 1 \text{ kHz}$$

The 3dB bandwidth for a 2nd order filter is given by:

$$B = \omega_0 / Q \Rightarrow Q = \frac{2\pi 10^3}{2\pi 50} = 20$$

Choose $C = 10 \text{ nF}$

$$R = \frac{1}{\omega_0 C} = 15.92 \text{ k}\Omega$$

$$\text{Use } R_1 = R_f = 10 \text{ k}\Omega$$

CONT.

$$\frac{R_3}{R_2} = 2Q - 1 = 39$$

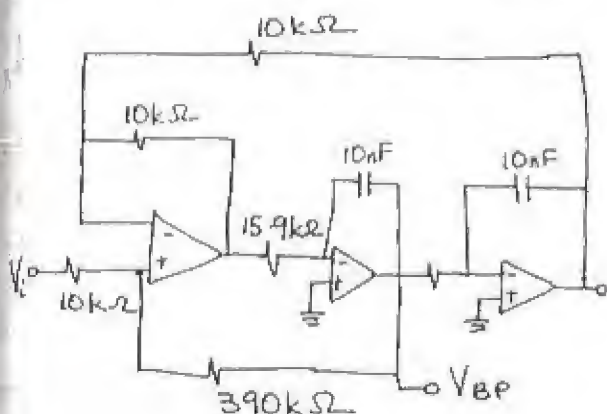
choose $R_2 = 10k\Omega$ $R_3 = 390k\Omega$

$$\text{Now } T(s) = \frac{-k\omega_0 s}{s^2 + s\frac{\omega_0}{Q} + \omega_0^2}$$

$$\Rightarrow |T(j\omega_0)| = \frac{k\omega_0^2}{\omega_0^2/Q} = kQ$$

but $k = 2 - 1/Q = 1.95$

\therefore Centre-freq gain = $kQ = 39$



Part (b) - $\omega_0 = 10^4$ rad/s $Q = 2$ Flat Gain = 10

choose $C = 10nF \Rightarrow R = \frac{1}{\omega_0 C} = 10k\Omega$

choose $R_F = R_1 = 10k\Omega$

$$\frac{R_3}{R_2} = 2Q - 1 = 3 \Rightarrow \frac{R_2}{R_3} = \frac{10k\Omega}{30k\Omega}$$

Now $k = 2 - 1/Q = 1.5$

\therefore Flat Gain = $10 = (1.5) \frac{R_F}{R_H}$

$\therefore \frac{R_H}{R_F} = 0.15$

choose $R_F = 100k\Omega$

$$R_H = R_L = 15k\Omega$$

$$R_B = QR_H = 30k\Omega$$

12.51

Note ω_n does not depend on R or C
From eq. 12.67:

$$\frac{R_H}{R_L} = \left(\frac{\omega_n}{\omega_0} \right)^2$$

$\therefore \omega_n = \omega_0 \sqrt{\frac{R_H}{R_L}}$ Nominally $R_H = R_L \pm 1\%$

Thus:

$$\omega_n' = \omega_0 \sqrt{\frac{1.01}{0.99}} = 1.01\omega_0 \quad \omega_n'' = \omega_0 \sqrt{\frac{0.99}{1.01}} = 0.99\omega_0$$

$\therefore \omega_n$ can deviate from ω_0
by $\pm 1\%$

12.50

$$R_L = R_H = R_B/Q \Rightarrow R_B = QR_H$$

$$R_L = R_H$$

Using Eq 12.66:

$$\frac{V_o}{V_i} = -k \frac{\frac{R_F}{R_H} s^2 - s\left(\frac{R_F}{R_B}\right)\omega_0 + \left(\frac{R_F}{R_L}\right)\omega_0^2}{s^2 + s\frac{\omega_0}{Q} + \omega_0^2}$$

$$= -k \frac{R_F}{R_H} \frac{s^2 - \frac{\omega_0}{Q}s + \omega_0^2}{s^2 + \frac{\omega_0}{Q}s + \omega_0^2}$$

Flat Gain = $-k R_F/R_H$

12.52

Use Tow Thomas to realize a LPN
(Fig 12.26)

$$\omega_0 = 10^4 \quad \omega_n = 1.2\omega_0 \quad Q=10 \quad \text{DC gain}=1$$

$$C = 10 \text{ nF} \quad r = 20 \text{ k}\Omega$$

$$R = \frac{1}{\omega_0 C} = \underline{\underline{10 \text{ k}\Omega}}$$

from 12.16(e):

$$\text{DC Gain} = a_2 \frac{\omega_n^2}{\omega_0^2} = 1$$

$$a_2 \frac{1.2^2 \omega_0^2}{\omega_0^2} = 1$$

$$a_2 = \frac{1}{1.2^2} = \text{HF Gain}$$

$$C_1 = C a_2 = \frac{10 \times 10^{-9}}{1.2^2} = \underline{\underline{6.94 \text{ nF}}}$$

$$R_2 = \frac{R (\omega_0/\omega_n)^2}{\text{HF Gain}} = R \left(\frac{1}{1.2}\right)^2 \times (1.2)^2$$

$$= R = \underline{\underline{10 \text{ k}\Omega}}$$

$$\underline{\underline{R_1 = R_3 = \infty}}$$

$$Q_z = \frac{\sqrt{\frac{1}{C^2 R R_2} \frac{C}{C_1}}}{\frac{1}{C} \left(\frac{1}{R_1} - \frac{r}{R R_3} \right) \left(\frac{C}{C_1} \right)}$$

$$= \frac{1}{\sqrt{R R_2} \left(\frac{1}{R_1} - \frac{r}{R R_3} \right) \sqrt{\frac{C}{C_1}}}$$

For All Pass $R_1 \rightarrow \infty$

To adjust Q_z , trim r or R_2
(independent of ω_z !)

Now $\omega_0 = \frac{1}{CR}$ so do not trim R or C !

Note if we trim R_2 or C_1 to adjust ω_z ,
this will also affect Q_z . So the
options are:

For ω_z : (a) trim R_2 AND (r or R_3) to
maintain the value of Q_z
OR

(b) trim C_1 , and r or R_3

Prefer not to trim a capacitor so
use (a)!

12.53

For all pass:

$$T(s) = \frac{-\frac{s^2(C_1)}{C} + s \frac{1}{C} \left(\frac{1}{R_1} - \frac{r}{R R_3} \right) + \frac{1}{C^2 R R_2}}{s^2 + s \frac{\omega_0}{Q} + \omega_0^2}$$

$$\omega_z^2 = \frac{1}{C^2 R R_2} \cdot \frac{C}{C_1} \Rightarrow \omega_z = \frac{1}{C \sqrt{R R_2}} \cdot \sqrt{\frac{C}{C_1}}$$

$$Q_z = \frac{\omega_z}{\frac{1}{C} \left(\frac{1}{R_1} - \frac{r}{R R_3} \right) \frac{C}{C_1}}$$

12.54

$$T(s) = \frac{0.4508 (s^2 + 1.6996)}{(s + 0.7294) (s^2 + 0.2786s + 1.0504)}$$

Part (a) Replace s with s/ω_p
 $\omega_p = 10^4 \text{ rad/s}$.

$$T(s) = \frac{0.4508 (s^2/\omega_p^2 + 1.6996)}{\left(\frac{s}{\omega_p} + 0.7294 \right) \left(\frac{s^2}{\omega_p^2} + \frac{0.2786s}{\omega_p} + 1.0504 \right)}$$

CONT.

$$T(s) = \frac{0.4508 \omega_p (s^2 + 1.6996 \omega_p^2)}{(s + 0.7294 \omega_p)(s^2 + 0.2786 \omega_p s + 1.0504 \omega_p^2)}$$

$$= \frac{4508 (s^2 + 1.6996 \times 10^8)}{(s + 7294)(s^2 + 2786s + 1.0504 \times 10^8)}$$

For First Order Section use Fig 12.13(a)

$$\omega_0 = 7294 \quad \text{Dc gain} = 1$$

$$\text{choose } C = 10 \text{ nF}$$

$$R_1 = R_2 = \frac{1}{\omega_0 C} \Rightarrow R_1 = R_2 = 13.71 \text{ k}\Omega$$

For Second Order Section - use Fig 12.26

$$\omega_n^2 = 1.6996 \times 10^8 \Rightarrow \omega_n = 13.037 \times 10^3$$

$$\omega_0^2 = 1.0504 \times 10^8 \Rightarrow \omega_0 = 10.249 \times 10^3$$

$$\frac{\omega_0}{Q} = 2786 \Rightarrow Q = 3.6787$$

$$\text{Dc gain} = 1$$

For Tow Thomas LPN use table 12.2

$$\text{choose } C = 10 \text{ nF}$$

$$R = \frac{1}{\omega_0 C} = \frac{1}{10.249 \times 10^3 \times 10 \times 10^{-9}}$$

$$= 9.757 \text{ k}\Omega$$

$$\text{choose } r = 20 \text{ k}\Omega$$

Now from Fig 12.16 (e):

$$T(\omega) = a_2 \frac{\omega_n^2}{\omega_0^2} = 1 \Rightarrow a_2 = \frac{\omega_0^2}{\omega_n^2} = 0.618$$

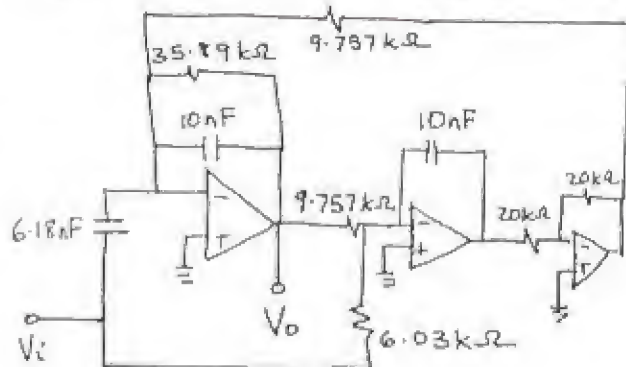
$$\therefore \text{HF gain} = a_2 = 0.618$$

$$C_1 = C \times \text{HF gain} \Rightarrow C_1 = 6.18 \text{ nF}$$

$$R_2 = R \left(\frac{\omega_0}{\omega_n} \right)^2$$

$$R_2 = 0.618 R \Rightarrow R_2 = 6.03 \text{ k}\Omega$$

$$R_1 = R_3 = \infty \quad QR = 35.89 \text{ k}\Omega$$



12.55

$$\text{Make } C_1 = C_2 = 1 \text{ nF} = C$$

$$\omega_0 = \frac{1}{\sqrt{C_1 C_2 R_3 R_4}} \quad Q = \left[\frac{\sqrt{C_1 C_2 R_3 R_4}}{R_3} \left(\frac{1}{C_1} + \frac{1}{C_2} \right) \right]$$

$$\text{Let } R_3 = R \quad m = 4Q^2$$

$$R_4 = \frac{R}{m} = \frac{4}{2} = 2$$

$$\therefore \omega_0 = \frac{1}{\sqrt{C^2 R^2/2}} = \frac{\sqrt{2}}{RC} = 10^4$$

$$\Rightarrow R = \frac{\sqrt{2}}{10^4 \times 10^{-9}} = 141.42 \text{ k}\Omega$$

$$R_3 = 141.4 \text{ k}\Omega$$

$$R_4 = \frac{R_3}{2} \Rightarrow R_4 = 70.7 \text{ k}\Omega$$

12.56

For Fig 12.28(a)

$$t(s) = \frac{s^2 + s\left(\frac{1}{C_1} + \frac{1}{C_2}\right)\frac{1}{R_3} + \frac{1}{C_1 C_2 R_3 R_4}}{s^2 + s\left(\frac{1}{C_1 R_3} + \frac{1}{C_1 R_4} + \frac{1}{C_2 R_3}\right) + \frac{1}{C_1 C_2 R_3 R_4}}$$

But $C_1 = C_2 = C$ & $R_3 = R_4 = R$, $RC = \tau$

$$\begin{aligned} \therefore t(s) &= \frac{s^2 + s^2/RC + 1/R^2 C^2}{s^2 + s^3/RC + 1/R^2 C^2} \\ &= \frac{s^2 + s^2/\tau + 1/\tau^2}{s^2 + s^3/\tau + 1/\tau^2} \end{aligned}$$

Zeros defined by $\omega_z = 1/\tau$
 $Q_z = \frac{1}{2}$ \Rightarrow Double Root at $s = -1/\tau$ Poles of $t(s)$ are given by the quadratic formula:

$$s = \frac{-3}{2\tau} \pm \frac{\sqrt{5}}{2\tau} = \frac{-3 \pm \sqrt{5}}{2\tau}$$

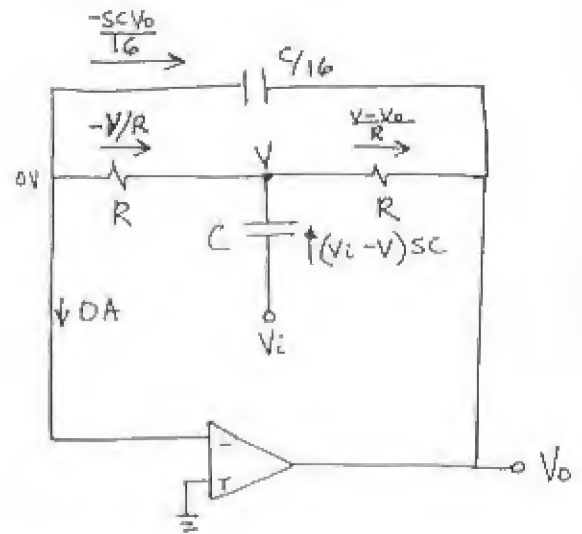
i.e. two roots on the negative real axis

If the network is placed in the negative feedback path of an ideal amplifier ($A = \infty$) then the poles are given by the zeros of $t(s)$:

Closed loop poles:

$$s = -1/\tau \quad (\text{multiplicity} = 2)$$

12.57

Note first $-\frac{sCV_o}{16} = -\frac{V}{R}$

$$V = -\frac{sCRV_o}{16}$$

 ΣI at V

$$-\frac{V}{R} + sc(V_i - V) - \frac{V - V_o}{R} = 0$$

$$\frac{sCV_o R}{16} + scV_i + s^2 C^2 R \frac{V_o}{16} + \frac{sCV_o}{16} + \frac{V_o}{R} = 0$$

mult by: $16R$ and let $RC = \tau$

$$s\tau V_o + 16\tau V_i s + s^2 \tau^2 V_o + s\tau V_o + 16V_o = 0$$

$$V_o [s^2 \tau^2 + s \cdot 2\tau + 16] = -16s\tau V_i$$

$$\therefore \frac{V_o}{V_i} = -\frac{16s\tau}{s^2 \tau^2 + 2\tau s + 16}$$

$$\therefore T(s) = \frac{s \cdot 16/RC}{s^2 + s^2/RC + 16/RC^2}$$

CONT.

$$\text{Let } \omega_0^2 = \frac{16}{(RC)^2} \Rightarrow \omega_0 = \frac{4}{RC}$$

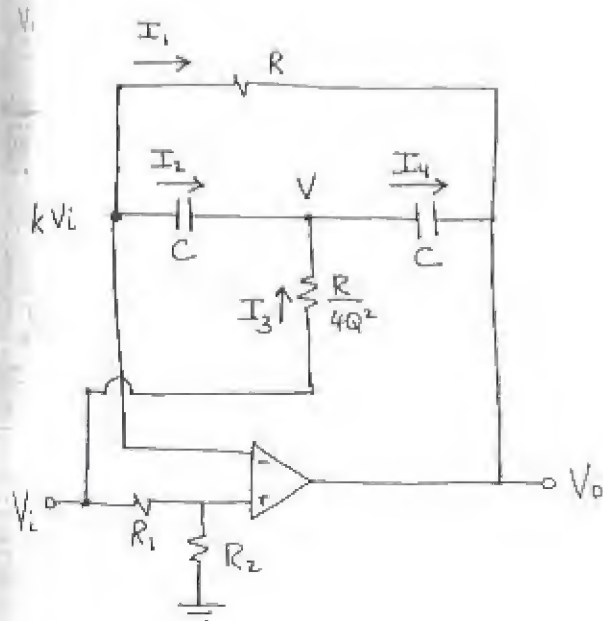
$$\frac{\omega_0}{Q} = \frac{2}{RC} \Rightarrow Q = \frac{RC\omega_0}{2} = \underline{\underline{2}}$$

$$\therefore \frac{V_o}{V_i} = \frac{-4\omega_0 s}{s^2 + s \frac{\omega_0}{Q} + \omega_0^2}$$

$$\left. \begin{array}{l} |T|_{s=0} = 0 \\ |T|_{s=\infty} = 0 \end{array} \right\} \text{Bandpass}$$

$$|T(j\omega_0)| = 4/1/2 = 8 \frac{V}{V} = \underline{\underline{\text{CENTRE FREQ GAIN}}}$$

12.58



$$RC = 2Q/\omega_0$$

$$k = \frac{R_1}{R_1 + R_2}$$

$$V_{+ve} = V_{-ve} = kV_i \quad \text{due to virtual short}$$

$$I_1 = -I_2$$

$$\frac{kV_i - V_o}{R} = \frac{V - kV_i}{1} (sc)$$

$$V = \frac{1}{sCR} (kV_i - V_o + sCR kV_i)$$

$$\sum I \text{ at } V = 0$$

$$I_2 + I_3 - I_4 = 0$$

$$sc(kV_i - V) + \frac{4Q^2}{R} (V_i - V) - sc(V - V_o) = 0$$

$$sc\left(kV_i - \frac{kV_i}{sCR} + \frac{V_o}{sCR} - kV_i\right)$$

$$+ \frac{4Q^2}{R} \left(V_i - \frac{kV_i}{sCR} + \frac{V_o}{sCR} - kV_i\right)$$

$$- sc\left(\frac{kV_i}{sCR} - \frac{V_o}{sCR} + kV_i - V_o\right) = 0$$

\Rightarrow

$$-\frac{kV_i}{R} + \frac{V_o}{R}$$

$$+ \frac{4Q^2}{R} \left(V_i - \frac{kV_i}{sCR} + \frac{V_o}{sCR} - kV_i\right)$$

$$- \frac{sC}{R} \left(\frac{kV_i}{sc} - \frac{V_o}{sc} + kRV_i - V_oR\right) = 0$$

$$\Rightarrow \text{SUB } CR = \frac{2Q}{\omega_0} \quad \& \quad R = \frac{2Q}{C\omega_0}$$

$$\begin{aligned} & -kV_i + V_o \\ & + 4Q^2 V_i - \frac{2Q^2 kV_i \omega_0}{s \& R} + \frac{V_o \omega_0^2 2Q^2}{s \& R} - 4Q^2 V_i \\ & - kV_i + V_o - s \& \frac{2Q}{\omega_0} V_i + s V_o \frac{2Q}{\omega_0} = 0 \end{aligned}$$

$$V_o \left[1 + \frac{2Q\omega_0}{s} + 1 + \frac{2Qs}{\omega_0} \right]$$

$$= V_i \left[k - 4Q^2 + \frac{2kQ\omega_0}{s} + 4Q^2k + k + \frac{2kQs}{\omega_0} \right]$$

$$\Rightarrow V_o \left[s^2 \frac{2Q}{\omega_0} + 2s + 2Q\omega_0 \right] = V_i \left[s^2 \frac{2kQ}{\omega_0} + s(4Q^2k - 4Q^2 + 2k) + 2kQ\omega_0 \right]$$

$$\Rightarrow \frac{V_o}{V_i} = \frac{s^2 \frac{2kQ}{\omega_0} + s(4Q^2k - 4Q^2 + 2k) + 2kQ\omega_0}{s^2 \frac{2Q}{\omega_0} + 2s + 2Q\omega_0}$$

$$= k \frac{s^2 + s \frac{\omega_0}{Q} (2Q^2 - \frac{2Q^2}{k} + 1) + \omega_0^2}{s^2 + s \frac{\omega_0}{Q} + \omega_0^2}$$

Recall $k = \frac{R_2}{R_1 + R_2}$ and $\frac{1}{k} = 1 + \frac{R_1}{R_2}$

$$\Rightarrow \frac{V_o}{V_i} = \left(\frac{R_2}{R_1 + R_2} \right) \frac{s^2 + s \frac{\omega_0}{Q} \left(1 - \frac{R_1}{R_2} \cdot 2Q^2 \right) + \omega_0^2}{s^2 + s \frac{\omega_0}{Q} + \omega_0^2}$$

$$\therefore T(s) = \frac{R_2}{R_1 + R_2} \frac{s^2 + s \frac{\omega_0}{Q} \left(1 - \frac{2Q^2 R_1}{R_2} \right) + \omega_0^2}{s^2 + s \frac{\omega_0}{Q} + \omega_0^2}$$

For All Pass

we want $T(s) \propto \frac{s^2 + \frac{\omega_0}{Q}(-1)s + \omega_0^2}{s^2 + s \frac{\omega_0}{Q} + \omega_0^2}$

$$\Rightarrow 1 - \frac{2Q^2 R_1}{R_2} = -1$$

$$\frac{2Q^2 R_1}{R_2} = 2$$

$$\frac{R_1}{R_2} = \frac{1}{Q^2}$$

$$\therefore \frac{R_2}{R_1} = Q^2 \quad \& \quad \frac{R_2}{R_1 + R_2} = \frac{R_2/R_1}{1 + R_2/R_1} = \frac{Q^2}{1 + Q^2}$$

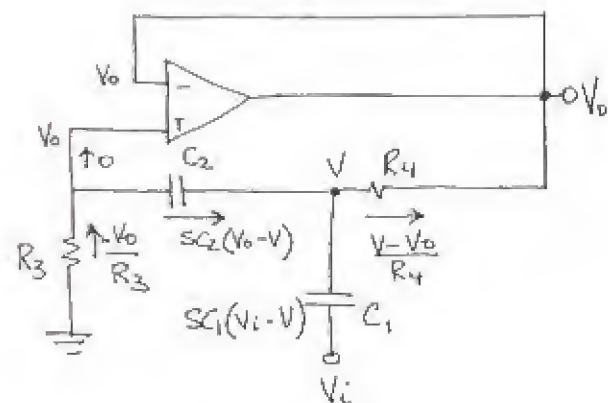
For Notch:

$$1 - \frac{2Q^2 R_1}{R_2} = 0$$

$$\frac{R_1}{R_2} = \frac{1}{2Q^2}$$

$$\frac{R_2}{R_1} = 2Q^2 \quad \& \quad \frac{R_2}{R_1 + R_2} = \frac{2Q^2}{1 + 2Q^2}$$

12.59



∴ No current can't flow into the terminal

$$-\frac{V_o}{R_3} = sC_2(V_o - V)$$

$$V = V_o \left(1 + \frac{1}{sC_2 R_3} \right)$$

CONT.

$$\sum I @ V = 0$$

$$-\frac{V_o}{R_3} + \frac{V_i - V}{1} sC_1 = \frac{V - V_o}{R_4}$$

$$V_o \left[-\frac{1}{R_3} + \frac{1}{R_4} \right] + V \left[-sC_1 - \frac{1}{R_4} \right] = -sC_1 V_i$$

$$V_o [R_4 - R_3] + V [sC_1 R_3 R_4 + R_3] = \frac{1}{s} sC_1 R_3 R_4$$

$$V_o (R_4 - R_3) + V_o \left(1 + \frac{1}{sC_2 R_3} \right) (sC_1 R_3 R_4 + R_3) = sC_1 R_3 R_4 V_i$$

$$V_o \left(R_4 - R_3 + sC_1 R_3 R_4 + R_3 + \frac{C_1}{C_2} R_4 + \frac{1}{sC_2} \right) = sC_1 R_3 R_4 V_i$$

$$V_o \left(s^2 C_1 C_2 R_3 R_4 + s C_1 R_4 + s C_2 R_4 + 1 \right) = s^2 C_1 R_3 R_4 C_2 V_i$$

$$\therefore \frac{V_o}{V_i} = \frac{s^2 C_1 C_2 R_3 R_4}{s^2 C_1 C_2 R_3 R_4 + s C_1 R_4 + s C_2 R_4 + 1}$$

$$= \frac{s^2}{s^2 + s \left(\frac{1}{C_1 R_3} + \frac{1}{C_1 R_3} \right) + \frac{1}{C_1 C_2 R_3 R_4}}$$

Note $|T(0)| = 0 \Rightarrow$ High Pass
 $|T(\infty)| = 1 \Rightarrow$ High Freq Gain = $\frac{1}{V_i}$

3dB freq = 10^3 rad/s, $Q = \frac{1}{\sqrt{2}}$ for max flat.

$\therefore \omega_0 = 10^3 \frac{\text{rad}}{\text{s}} \quad C_1 = C_2 = 10 \text{ nF}$

clearly $\omega_0^2 = \frac{1}{C_1 C_2 R_3 R_4}$ and

$$\frac{\omega_0}{Q} = \frac{1}{C_2 R_3} + \frac{1}{C_1 R_3} = \frac{C_1 + C_2}{C_1 C_2 R_3}$$

$$= \frac{2C}{C^2 R_3} = \frac{2}{C R_3} = \sqrt{2} \times 10^3$$

$$R_3 = \frac{2}{10 \times 10^{-9} \times 10^3 \times \sqrt{2}}$$

$$\underline{R_3 = 141.4 \text{ k}\Omega}$$

$$R_4 = \frac{1}{\omega_0^2 C_1 C_2 R_3} \Rightarrow \underline{R_4 = 70.7 \text{ k}\Omega}$$

12.60

$$A_{\max} = 3 \text{ dB}$$

$$\epsilon = \left(10^{\frac{3}{10}} - 1 \right)^{-\frac{1}{2}} \approx 1$$

$$\omega_0 = \omega_p \left(\frac{1}{\epsilon} \right)^{1/N} = \omega_p = 2\pi 5000 = 10^4 \pi$$

$$Q_1 = \frac{1}{2 \cos 36} = 0.618$$

$$Q_2 = \frac{1}{2 \cos 72} =$$

For first order section:

$$\omega_0 = 10^4 \pi \quad \text{dc gain} = 1$$

From 12.13 (a)

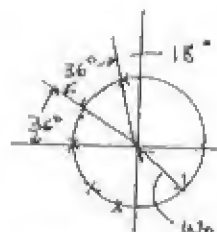
$$\underline{R_1 = R_2 = 10 \text{ k}\Omega}$$

$$C = \frac{1}{\omega_0 R_2} = \frac{1}{10^4 \pi \cdot 10^4} = \underline{3.18 \text{ nF}}$$

Second-Order Section $Q = 0.618$:

from 12.34 (c): $m = 4Q^2 = 1.528$

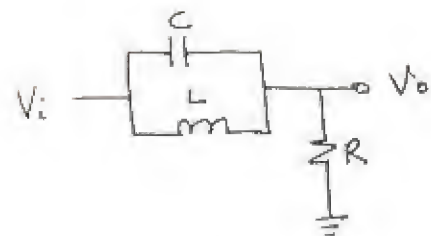
CONT.



$$RC = \frac{2Q}{\omega_0} \quad \text{let } R_1 = R_2 = 10k\Omega$$

$$C = \frac{2Q}{\omega_0 R} \Rightarrow C_4 = C = 3.93nF$$

$$C_3 = \frac{C}{m} = 2.57nF$$



this is the same as Fig 12.18(e)

Second Order Section $Q = 1.618$:

$$C = \frac{2Q}{\omega_0 R} \quad m = 4Q^2 = 10.472$$

$$= 10.3nF \Rightarrow R_1 = R_2 = 10k\Omega$$

$$C_4 = C = 10.3nF$$

$$C_3 = \frac{C}{m} = 0.984nF$$

12.62

for Fig 12.18(d):

$$T(s) = \frac{s/RC}{s^2 + s/RC + 1/LC}$$

$$\omega_0 = \frac{1}{\sqrt{LC}} \quad Q = R\sqrt{\frac{C}{L}}$$

12.61

For a bandpass filter

$$T(s) = \frac{\omega_0/Q s}{s^2 + s\omega_0/Q + \omega_0^2}$$

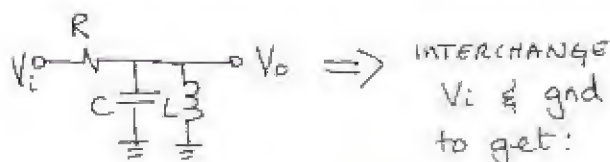
centre freq. gain = 1

complementary transfer function:

$$T' = 1 - T$$

$$= \frac{s^2 + \omega_0^2}{s^2 + s\omega_0/Q + \omega_0^2} \equiv \text{NOTCH!}$$

From Fig 12.18(d)



For ω_0

$$\frac{\partial \omega_0}{\partial L} = \frac{\partial (LC)^{-1/2}}{\partial L} = -\frac{1}{2} L^{-3/2} C^{-1/2} = -\frac{\omega_0}{2L}$$

$$\frac{\partial \omega_0}{\partial C} = -\frac{\omega_0}{2C}$$

$$\frac{\partial \omega_0}{\partial R} = 0$$

$$\therefore S_L^{\omega_0} = \frac{\partial \omega_0}{\partial L} \frac{L}{\omega_0} = -\frac{1}{2}$$

$$S_C^{\omega_0} = \frac{\partial \omega_0}{\partial C} \times \frac{C}{\omega_0} = -\frac{1}{2}$$

$$S_R^{\omega_0} = \frac{\partial \omega_0}{\partial R} \frac{R}{\omega_0} = 0$$

For Q

$$\frac{\partial Q}{\partial L} = \frac{R\sqrt{C}}{L\sqrt{L}} \left(-\frac{1}{2}\right)$$

$$\frac{\partial Q}{\partial C} = \frac{1}{2} \frac{R}{\sqrt{LC}} = \frac{1}{2} \frac{R\sqrt{C}}{C\sqrt{L}} = \frac{Q}{2C}$$

$$\frac{\partial Q}{\partial R} = \sqrt{C/L} = \frac{R}{R} \sqrt{C/L} = Q/R$$

CONT.

$$S_L^Q = \frac{-Q}{2L} \cdot \frac{L}{Q} = \underline{\underline{-\frac{1}{2}}}$$

$$S_C^Q = \frac{Q}{2C} \cdot \frac{C}{Q} = \underline{\underline{\frac{1}{2}}}$$

$$S_R^Q = \frac{Q}{R} \cdot \frac{R}{Q} = \underline{\underline{1}}$$

12.63

$$y = uv$$

$$\begin{aligned} S_x^y &= \frac{\partial(uv)}{\partial x} \cdot \frac{x}{uv} \\ &= v \frac{\partial u}{\partial x} \frac{x}{uv} + u \frac{\partial v}{\partial x} \frac{x}{uv} \\ &= \frac{\partial u}{\partial x} \frac{x}{u} + \frac{\partial v}{\partial x} \frac{x}{v} \\ &= \underline{\underline{S_x^u + S_x^v}} \end{aligned}$$

Part (b) $y = u/v$

$$\begin{aligned} S_x^y &= \frac{\partial y}{\partial x} \cdot \frac{x}{y} = \frac{\partial(u/v)}{\partial x} \cdot \frac{xv}{u} \\ &= \frac{1}{v} \frac{\partial u}{\partial x} \frac{xv}{u} + \frac{-u}{v^2} \frac{\partial v}{\partial x} \cdot \frac{xv}{u} \\ &= \frac{\partial u}{\partial x} \frac{x}{u} - \frac{\partial v}{\partial x} \frac{x}{v} \\ &= \underline{\underline{S_x^u - S_x^v}} \end{aligned}$$

Part (c) $y = ku$

$$\begin{aligned} S_x^y &= \frac{\partial y}{\partial x} \cdot \frac{x}{y} = \frac{\partial(ku)}{\partial x} \cdot \frac{x}{ku} \\ &= k \frac{\partial u}{\partial x} \frac{x}{ku} \\ &= \frac{\partial u}{\partial x} \frac{x}{u} \\ &= \underline{\underline{S_x^u}} \end{aligned}$$

Part (d) $y = u^n$

$$\begin{aligned} S_x^y &= \frac{\partial y}{\partial x} \cdot \frac{x}{y} = \frac{\partial(u^n)}{\partial x} \cdot \frac{x}{u^n} \\ &= n u^{n-1} \frac{\partial u}{\partial x} \cdot \frac{x}{u^n} \\ &= n \frac{\partial u}{\partial x} \frac{x}{u} = \underline{\underline{n S_x^u}} \end{aligned}$$

Part (e) $y = f_1(u)$ $u = f_2(x)$

$$\begin{aligned} S_x^y &= \frac{\partial y}{\partial x} \cdot \frac{x}{y} = \frac{\partial f_1(u)}{\partial x} \cdot \frac{x}{f_1(u)} \\ &= \frac{\partial f_1(u)}{\partial u} \frac{\partial u}{\partial x} \cdot \frac{x}{f_1(u)} \\ &= \frac{\partial f_1}{\partial u} \cdot \frac{\partial f_2}{\partial x} \cdot \frac{x}{f_1} \cdot \frac{u}{u} \end{aligned}$$

But $u = f_2$

$$\begin{aligned} \therefore S_x^y &= \frac{\partial f_1}{\partial u} \cdot \frac{\partial f_2}{\partial x} \cdot \frac{x}{f_1} \cdot \frac{u}{f_2} \\ &= \frac{\partial f_1}{\partial u} \cdot \frac{u}{f_1} \cdot \frac{\partial f_2}{\partial x} \frac{x}{f_2} \\ &= S_u^{f_1} \cdot S_x^{f_2} \\ &= \underline{\underline{S_u^y S_x^u}} \end{aligned}$$

12.64

Since the characteristic equation of Fig. 12-33(b) is the same as for Fig. 12-29 the poles are given by Eq. 12-86:

$$s^2 + s \frac{\omega_0}{Q} \left[1 + \frac{2Q^2}{A+1} \right] + \omega_0^2 = 0$$

This is because 12-33(b) is based on the complementary transform of 12-29 and hence the pole

locations are preserved!

Now the actual w_0 and Q are given by:

$$w_{0,a} = w_0 \quad \text{and} \quad Q_a = \frac{Q}{1 + \frac{2Q^2}{(A+1)}}$$

Thus from Ex. 12.3

$$S_A^{w_{0,a}} = \underline{\underline{0}}$$

$$S_A^{Q_a} = \frac{A}{A+1} \cdot \frac{2Q^2/(A+1)}{1 + 2Q^2/(A+1)}$$

$$\therefore S_A^{Q_a} \approx \underline{\underline{\frac{2Q^2}{A}}}$$

12.65

If $R_1 = R_2$, then from (12.77) & (12.78)

$$w_0 = \frac{1}{\sqrt{C_3 C_4 R_1 R_2}}$$

$$Q = \frac{1}{\sqrt{C_3 C_4 R_1 R_2} \left(\frac{1}{C_4} \right) \left(\frac{1}{R_1} + \frac{1}{R_2} \right)}$$

$$\frac{\partial w_0}{\partial C_3} = \frac{-1}{2C_3 \sqrt{C_3 C_4 R_1 R_2}}$$

$$\frac{\partial w_0}{\partial C_3} = \frac{-1}{2C_3 \sqrt{C_3 C_4 R_1 R_2}} = -\frac{w_0}{2C_3}$$

$$S_{C_3}^{w_0} = \frac{\partial w_0}{\partial C_3} \frac{C_3}{w_0} = \underline{\underline{-\frac{1}{2}}}$$

$$\text{clearly } S_{C_3}^{w_0} = S_{C_4}^{w_0} = S_{R_1}^{w_0} = S_{R_2}^{w_0} = -\frac{1}{2}$$

$$\frac{\partial Q}{\partial C_3} = \frac{-1}{2C_3 \sqrt{C_3 C_4 R_1 R_2} \left(\frac{1}{C_4} \right) \left(\frac{1}{R_1} + \frac{1}{R_2} \right)} = \frac{-Q}{2C_3}$$

$$\therefore S_{C_3}^Q = \underline{\underline{-\frac{1}{2}}}$$

$$\frac{\partial Q}{\partial C_4} = \frac{Q}{2C_4} \Rightarrow S_{C_4}^Q = \underline{\underline{+\frac{1}{2}}}$$

$$\begin{aligned} \frac{\partial Q}{\partial R_1} &= \frac{\frac{1}{\sqrt{R_1}} - \sqrt{R_1}/R_2}{R_1 \left(\frac{1}{\sqrt{R_1}} + \sqrt{R_1}/R_2 \right)} \cdot \frac{Q}{2} \\ &= \frac{\sqrt{R_2/R_1} - \sqrt{R_1/R_2}}{R_1 \left(\sqrt{R_2/R_1} + \sqrt{R_1/R_2} \right)} \cdot \frac{Q}{2} \end{aligned}$$

$$\therefore S_{R_1}^Q = \frac{\sqrt{R_2/R_1} - \sqrt{R_1/R_2}}{\sqrt{R_2/R_1} + \sqrt{R_1/R_2}}$$

$$\text{if } R_1 = R_2 \Rightarrow S_{R_1}^Q = 0 \quad \& \quad S_{R_2}^Q = 0$$

12.66

From table 12.1

$$w_0 = \frac{1}{\sqrt{C_4 C_6 R_1 R_3 R_5 / R_2}}$$

$$Q = R_6 \sqrt{\frac{C_6}{C_4} \frac{R_2}{R_1 R_3 R_5}}$$

$$\frac{\partial w_0}{\partial C_4} = \frac{-w_0}{2C_4}$$

$$\therefore S_{C_4}^{w_0} = \frac{-w_0}{2C_4} \times \frac{C_4}{w_0} = \underline{\underline{-\frac{1}{2}}}$$

$$\text{Similarly } S_{C_6}^{w_0} = S_{R_1}^{w_0} = S_{R_3}^{w_0} = S_{R_5}^{w_0} = \underline{\underline{-\frac{1}{2}}}$$

$$\frac{\partial w_0}{\partial R_2} = \frac{w_0}{2R_2} \Rightarrow S_{R_2}^{w_0} = \underline{\underline{\frac{1}{2}}}$$

Now for Q :

$$\frac{\partial Q}{\partial R_6} = \frac{Q}{R_6} \Rightarrow S_{R_6}^Q = \frac{\partial Q}{\partial R_6} \frac{R_6}{Q} = \underline{\underline{+1}}$$

CONT.

$$\frac{\partial Q}{\partial C_6} = \frac{Q}{2C_6} \Rightarrow \int_{C_6}^Q = \int_{R_2}^Q = \underline{\underline{+\frac{1}{2}}}$$

$$\frac{\partial Q}{\partial C_4} = \frac{-Q}{2C_4} \Rightarrow \int_{C_4}^Q = \int_{R_1, R_3, R_5}^Q = \underline{\underline{-\frac{1}{2}}}$$

12.67

$$R_{eq} = \frac{T_c}{C_1} = \frac{1/100 \times 10^3}{C_1}$$

$$\text{for } 1\text{pF} \rightarrow R_{eq} = 10^{-5}/10^{-12} = \underline{\underline{10\text{M}\Omega}}$$

$$\text{for } 10\text{pF} \rightarrow R_{eq} = 10^{-5}/10 \times 10^{-12} = \underline{\underline{1\text{M}\Omega}}$$

12.68

$$\begin{aligned} \text{charge transferred} \Rightarrow Q &= CV \\ &= 10^{-12}(1) \\ &= \underline{\underline{1\text{pC}}} \end{aligned}$$

For $f_0 = 100\text{kHz}$, average current is given by:

$$\begin{aligned} I_{AVE} &= \frac{Q}{T} = 1\text{pC} \times \frac{1}{100 \times 10^3} \\ &= \underline{\underline{0.1\mu\text{A}}} \end{aligned}$$

For each clock cycle, the output will change by the same amount as the change in voltage across C_2 !

$$\therefore \Delta V = Q/C_2 = \frac{1\text{pC}}{10\text{pF}} = \underline{\underline{0.1\text{V}}}$$

For $\Delta V = 0.1\text{V}$ for each clock cycle, the amplifier will saturate in

$$\# \text{cycles} = \frac{10\text{V}}{0.1\text{V}} = \underline{\underline{100 \text{ cycles}}}$$

$$\begin{aligned} \text{slope} &= \frac{\Delta V}{\Delta t} = \frac{10\text{V}}{(100 \text{ cycles}) (1/100 \times 10^3)} \\ &= \underline{\underline{10^4 \frac{\text{V}}{\text{s}}}} \end{aligned}$$

12.69

$$f_c = 400\text{kHz} \quad f_0 = 10\text{kHz} \quad Q = 20$$

$$C_1 = C_2 = 20\text{pF} = C$$

$$\begin{aligned} C_3 = C_4 &= \omega_0 T_c C = 2\pi(10^4) \frac{1}{400 \times 10^3} 20 \times 10^{-12} \\ &= \underline{\underline{3.14\text{pF}}} \end{aligned}$$

$$C_5 = \frac{\omega_0 T_c C}{Q}$$

$$= \frac{C_3}{Q} = \underline{\underline{0.157\text{pF}}}$$

$$\begin{aligned} C_6 &= \frac{\omega_0 T_c C}{Q} \times \text{center frequency gain} \\ &= \underline{\underline{0.157\text{pF}}} \end{aligned}$$

Note that the clock frequency has doubled. Hence the period, T_c , is halved. Therefore, for the same integrating capacitors, the resistors (switched capacitors) will change by the factor of 2. So compensate for this by changing the switched caps by a factor of $1/2$.

12.70

$$\text{Ex 12.31 for } Q = 40 \quad f_c = 200\text{kHz} \\ f_0 = 10\text{kHz}$$

$$C_1 = C_2 = 20\text{pF} = C$$

$$\begin{aligned} C_3 = C_4 &= \omega_0 T_c C \\ &= 2\pi(10^4) \left(\frac{1}{200 \times 10^3} \right) 20 \times 10^{-12} \\ &= \underline{\underline{6.28\text{pF}}} \end{aligned}$$

CONT.

$$C_B = \frac{\omega_0 T_c C}{Q} = \frac{C_3}{Q} = \underline{\underline{0.157 \text{ pF}}}$$

$$C_6 = \frac{\omega_0 T_c C}{Q} = C_5 = \underline{\underline{0.157 \text{ pF}}}$$

12.71

$$\omega_0 = 10^4, Q = 1/\sqrt{2}, f_c = 100 \text{ kHz}$$

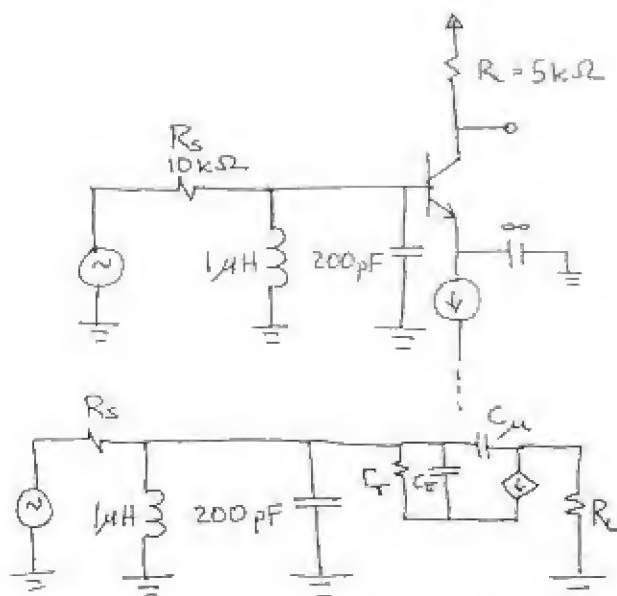
$$\text{DC gain} \Rightarrow \frac{R_4}{R_6} \Rightarrow \frac{C_6}{C_4} = 1$$

$$C_1 = C_2 = 10 \text{ pF}$$

$$\begin{aligned} C_3 = C_4 = C_6 &= \omega_0 T_c C \\ &= 10^4 \left(\frac{1}{100 \times 10^3} \right) 10 \times 10^{-12} \\ &= \underline{\underline{1 \text{ pF}}} \end{aligned}$$

$$C_B = C_4/Q = \underline{\underline{1.41 \text{ pF}}}$$

12.72



$$\begin{aligned} r_e &= 25 \Omega, C_\mu = 1 \text{ pF}, C_\pi = 10 \text{ pF}, \beta = 200 \\ r_\pi &= (\beta + 1) r_e = 5.025 \text{ k}\Omega \end{aligned}$$

From base to collector

$$\frac{V_c}{V_b} = -\frac{\beta}{\beta + 1} \cdot \frac{R_c}{r_e} = -199 = k$$

Total capacitance at base

$$\begin{aligned} C_T &= C_\pi + 200 \text{ pF} + C_\mu (1 - k) \quad \leftarrow \text{Miller Effect} \\ &= 10 + 200 + 1(1 + 199) \\ &= 410 \text{ pF} \end{aligned}$$

$$\begin{aligned} \therefore \omega_0 &= \frac{1}{\sqrt{L C}} \\ &= \frac{1}{\sqrt{10^{-6} \times 410 \times 10^{-12}}} \\ &= \underline{\underline{49.4 \times 10^6 \text{ rad/s}}} \end{aligned}$$

Centre frequency gain =

$$\begin{aligned} &\frac{r_\pi}{R_s + r_\pi} \cdot k \\ &= \frac{5.025}{10 + 5.025} \times -199 \\ &= \underline{\underline{-66.6 \text{ V/V}}} \end{aligned}$$

$$\begin{aligned} BW &= \frac{1}{RC} \\ &= \frac{1}{(R_s \parallel r_\pi) 410 \text{ pF}} \\ &= \underline{\underline{729 \times 10^3 \text{ rad/s}}} \end{aligned}$$

$$\begin{aligned} Q &= \frac{\omega_0}{BW} \\ &= 49.4 / 0.7293 \\ &= \underline{\underline{67.7}} \end{aligned}$$

12.73

$$Q_0 = \frac{R_p}{\omega_0 L} \Rightarrow R_p = Q_0 \omega_0 L$$

$$= 200 (2\pi \times 10^6) (10 \times 10^{-6})$$

$$= \underline{12.57 \text{ k}\Omega}$$

$$\omega_0 = \frac{1}{\sqrt{LC}} \Rightarrow C = \frac{1}{\omega_0^2 L}$$

$$= \frac{1}{(2\pi \times 10^6)^2 \times 10 \times 10^{-6}}$$

$$= \underline{2.533 \text{ nF}}$$

$$B = \frac{1}{RC} \quad R_r = \frac{1}{(2\pi \times 10 \times 10^3) (2.533 \times 10^{-7})}$$

$$= 6.283 \text{ k}\Omega$$

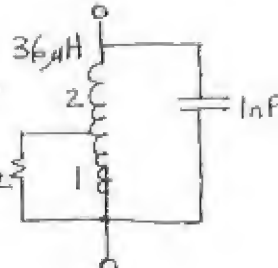
$$\therefore \frac{1}{R_1} + \frac{1}{R_p} = \frac{1}{R_r}$$

$$\Rightarrow R_1 = \underline{12.57 \text{ k}\Omega} \quad \text{i.e. } R_1 \parallel R_p = R_r$$

12.74

$$f_0 = \frac{1}{2\pi\sqrt{LC}}$$

$$= (2\pi(36 \times 10^{-9}) 10^{-9})^{-1}$$

$$= \underline{838.8 \text{ kHz}}$$


$$R_p = n^2 R$$

$$= 9 (1 \text{ k}\Omega)$$

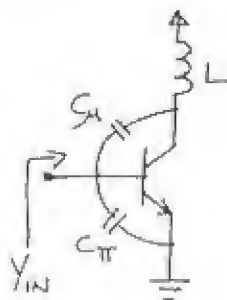
$$= 9 \text{ k}\Omega$$

$$Q = R_p / \omega_0 L$$

$$= \frac{9 \times 10^3}{2\pi \times 838.8 \times 10^3 \times 36 \times 10^{-6}}$$

$$= \underline{47.4}$$

12.75



$$\text{for } \omega C_{\mu} \ll \frac{1}{\omega L}$$

$$\therefore \omega^2 \ll \frac{1}{LC_{\mu}}$$

i.e. well below resonance

$$\therefore \text{gain} = -g_m(j\omega L)$$

$$\therefore Y_{in} = \frac{1}{r_{\pi}} + j\omega C_{\pi} + j\omega C_{\mu}(1 + g_m j\omega L)$$

$$= \left(\frac{1}{r_{\pi}} - \omega^2 g_m C_{\mu} L \right) + j\omega (C_{\pi} + C_{\mu})$$

AS REQUIRED!

12.76

From Fig. 12.16 (c):

$$T(s) = \frac{a_1 s}{s^2 + s \frac{\omega_0}{Q} + \omega_0^2}$$

$$T(j\omega) = \frac{j a_1 \omega}{\omega_0^2 - \omega^2 + j \omega \frac{\omega_0}{Q}}$$

$$T(j\omega_0) = \frac{j a_1 \omega_0}{j \omega_0^2 / Q} = \frac{a_1 Q}{\omega_0}$$

$$|T(j\omega)| = a_1 \omega \left[(\omega_0^2 - \omega^2)^2 + \left(\frac{\omega \omega_0}{Q} \right)^2 \right]^{-1/2}$$

$$= \frac{a_1 \omega}{\omega_0} \frac{Q}{\sqrt{1 + Q^2 \left(\frac{\omega_0^2 - \omega^2}{\omega_0 \omega} \right)^2}}$$

$$\text{Now } \omega = \omega_0 + \delta \omega, \quad \frac{\delta \omega}{\omega_0} \ll 1$$

$$\text{and } \omega^2 \approx \omega_0^2 \left(1 + 2 \frac{\delta \omega}{\omega_0} \right)$$

CONT.

$$\text{so } \omega_0^2 - \omega^2 = -2\delta\omega\omega_0$$

$$\therefore |T(j\omega)| \approx \frac{a_1 Q / \omega_0}{\sqrt{1 + Q^2 \left(\frac{2\delta\omega}{\omega}\right)^2}}$$

$$\text{for } Q \gg 1: Q^2 \left(\frac{2\delta\omega}{\omega}\right)^2 \approx Q^2 \left(\frac{2\delta\omega}{\omega_0}\right)^2$$

$\because \omega \approx \omega_0!$

$$\Rightarrow |T(j\omega)| \approx \frac{|T(j\omega_0)|}{\sqrt{1 + Q^2 \left(\frac{2\delta\omega}{\omega_0}\right)^2}}$$

$$= \frac{|T(j\omega_0)|}{\sqrt{1 + 4Q^2 \frac{\delta\omega^2}{\omega_0^2}}}$$

For N bandpass sections, synchronously tuned in cascade, half power is given by:

$$\left(\frac{1}{\sqrt{1 + 4Q^2 \left(\frac{\delta\omega}{\omega_0}\right)^2}} \right)^N = \frac{1}{\sqrt{2}}$$

$$\left(1 + 4Q^2 \left(\frac{\delta\omega}{\omega_0}\right)^2 \right)^N = 2$$

$$4Q^2 \left(\frac{\delta\omega}{\omega_0}\right)^2 = 2^{1/N} - 1$$

$$\delta\omega = \frac{\omega_0}{2Q} \sqrt{2^{1/N} - 1}$$

\therefore Bandwidth:

$$B = 2\delta\omega = \frac{\omega_0}{Q} \sqrt{2^{1/N} - 1}$$

12.77

For first order lowpass:

$$T(s) = \frac{\omega_0'}{s + \omega_0'} \quad |T(j\omega)| = \frac{\omega_0'}{\sqrt{\omega^2 + \omega_0'^2}}$$

for a bandpass response around ω_0 with $\omega_0' = \frac{\omega_0}{2Q}$:

$$|T(j\omega)| \approx \frac{\omega_0 / 2Q}{(\delta\omega)^2 + \left(\frac{\omega_0}{2Q}\right)^2}$$

$$= \frac{\omega_0 / 2Q}{\frac{\omega_0}{2Q} \sqrt{\left(\frac{2Q}{\omega_0}\right)^2 (\delta\omega)^2 + 1}}$$

$$= \frac{1}{\sqrt{1 + 4Q^2 \left(\frac{\delta\omega}{\omega_0}\right)^2}}$$

Now at $\omega = \omega_0$ or $\delta\omega = 0$
 $|T(j\omega_0)| = 1$, then

$$T(j\omega) \approx \frac{|T(j\omega_0)|}{\sqrt{1 + 4Q^2 \left(\frac{\delta\omega}{\omega_0}\right)^2}}$$

Part (b)

For N synchronously tuned sections in cascade; 3dB bandwidth is given by:

$$\left(|T| / |T_0| \right)^N = \frac{1}{\sqrt{2}}$$

$$\left(|T| / |T_0| \right)^2 = \frac{1}{2^{1/N}} \quad \text{OR}$$

$$1 + 4Q^2 \left(\frac{\delta\omega}{\omega_0}\right)^2 = 2^{1/N} \quad \text{OR}$$

$$2\delta\omega = \frac{\omega_0}{Q} \sqrt{2^{1/N} - 1} \quad (12.110)$$

CONT.

Thus: $|T(j\omega)|_{\text{overall}} = |T(j\omega)|^N$

$$= \frac{|T(j\omega_0)|_{\text{overall}}}{\left[1 + 4Q^2 \left(\frac{\delta\omega}{\omega_0}\right)^2\right]^{N/2}}$$

NOTE
 $Q = \frac{\omega_0}{B} \sqrt{2^{1/N} - 1}$

$$= \frac{|T(j\omega_0)|_{\text{overall}}}{\left(1 + 4 \frac{\omega_0^2}{B^2} (2^{1/N} - 1) \left(\frac{\delta\omega}{\omega_0}\right)^2\right)^{N/2}}$$

$$= \frac{|T(j\omega_0)|_{\text{overall}}}{\left[1 + 4 (2^{1/N} - 1) \left(\frac{\delta\omega}{B}\right)^2\right]^{N/2}}$$

Part (c) (i)

for bandwidth $= 2B$, i.e. $\delta\omega = \pm B$
Att = $-20 \log (1 + 4 (2^{1/N} - 1) (1)^2)^{N/2}$

$$= -10N \log (1 + 2^{2+1/N} - 4)$$

$$= 10N \log (2^{2+1/N} - 3)$$

N =	1	2	3	4	5
Att (dB)	6.70	8.44	9.28	9.79	10.13

Part (c) (ii)

3dB bandwidth $\delta\omega = \pm B/2$

30dB bandwidth $\frac{\delta\omega}{B} = x$

$$-30 = -20 \frac{N}{2} \log (1 + 4 (2^{1/N} - 1) x^2)$$

$$3 = N \log (1 + 4 (2^{1/N} - 1) x^2)$$

$$x = \left[\frac{10^{3/N} - 1}{4(2^{1/N} - 1)} \right]^{1/2}$$

Ratio of 30dB to 3dB

$$BW = \frac{2Bx}{B} = 2x$$

N =	1	2	3	4	5
Ratio =	31.6	8.6	5.7		4.5

12.78

See fig 12.48 and Eq 12.115 and 12.116

(a) For the narrowband approximation, variation of ω around 0 is equivalent to $\delta\omega$ around ω_0 . Thus, a low-pass maximally flat filter of bandwidth $B/2$ and order N for which $|T| = \left[1 + \left(\frac{\omega}{B/2}\right)^2\right]^{N/2}$

is transformed to a band-pass maximally flat filter of bandwidth $B/2$ and order $2N$, and centre frequency ω_0 , for which:

$$|T| = \left(1 + \left(\frac{\delta\omega}{B/2}\right)^2\right)^{-N/2}$$

(b) For bandwidth $2B$, $\delta\omega = B$ &

$$|T| = \left(1 + \left(\frac{B}{B/2}\right)^2\right)^{-N/2}$$

$$= (1 + 2^{2N})^{-N/2} \text{ thus:}$$

N	1	2	3	4	5
T	0.447	0.242	0.124	0.062	0.031
T _{dB}	-6.99	-12.3	-18.1	-24.1	-30.1

For 30 dB bandwidth,
 $-30 = 20 \log x \Rightarrow x = 10^{-3/2}$
 $= \frac{1}{31.6}$

$$1 + \left(\frac{s' \omega}{B/2} \right)^{2N} = (31.6)^2$$

$$\left(\frac{s' \omega}{B/2} \right)^{2N} = 999 - 1 = 998$$

Now the ratio of 30dB to 3dB bandwidths is

$$\text{ratio} = \frac{2s' \omega}{B} = \frac{s' \omega}{B/2} = 998^{\frac{1}{2N}}$$

N	1	2	3	4	5
ratio	31.6	5.62	3.16	2.37	1.99

12.79

$$A_{\max} = 3 \text{ dB} \Rightarrow \epsilon = \sqrt{10^{A_{\max}/10} - 1} \approx 1$$

Poles of lowpass prototype are given by FIG 12.10(c)

$$\text{Poles: } -\omega_p, \omega_p \left(-\frac{1}{2} \pm j\frac{\sqrt{3}}{2} \right)$$

$$\text{Make } \omega_p = B/2$$

$$\Rightarrow \text{poles: } \left\{ -\frac{B}{2}, +\frac{B}{2} \left(-\frac{1}{2} \pm j\frac{\sqrt{3}}{2} \right) \right\}$$

Using the low-pass to bandpass transformation:

Poles of the bandpass filter:

$$-\frac{B}{2} \pm j\omega_0,$$

$$-\frac{B}{4} \pm j \left(\frac{\sqrt{3}}{4} B + \omega_0 \right) \quad \text{and}$$

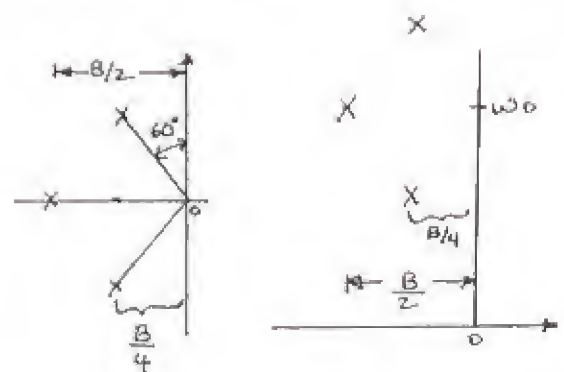
$$-\frac{B}{4} \pm j \left(\frac{\sqrt{3}}{4} B - \omega_0 \right)$$

For the three circuits:

$$\textcircled{1} \omega_{01} = \omega_0 \quad B_1 = B \quad Q_1 = \omega_0/B$$

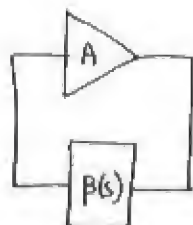
$$\textcircled{2} \omega_{02} \approx \frac{\sqrt{3}}{4} B + \omega_0 \quad B_2 = \frac{B}{2} \quad Q_2 \approx \frac{2\omega_0}{B}$$

$$\textcircled{3} \omega_{03} \approx \frac{\sqrt{3}}{4} B - \omega_0 \quad B_3 = \frac{B}{2} \quad Q_3 \approx \frac{2\omega_0}{B}$$



CHAPTER 13 - PROBLEMS

13.1



$$A = A_0 > 0$$

$$B(s) = \frac{k \frac{\omega_0}{Q} s}{s^2 + s \frac{\omega_0}{Q} + \omega_0^2}$$

(a) For oscillations $1 - AB(s) = 0$

$$\therefore A_0 k \frac{\omega_0}{Q} s = s^2 + s \frac{\omega_0}{Q} + \omega_0^2$$

$$\omega_0^2 - \omega^2 = j\omega \left(\frac{\omega_0}{Q} \right) (A_0 k - 1)$$

at the freq of oscillation, both Real & Imaginary parts are 0.

$$\therefore \underline{\omega = \omega_0} \quad \& \quad \underline{A_0 k = 1}$$

$$(b) \quad L(j\omega) \triangleq AB(j\omega) = \frac{A k \frac{\omega_0}{Q} j\omega}{(\omega_0^2 - \omega^2) + j\omega \left(\frac{\omega_0}{Q} \right)}$$

$$\therefore \phi(\omega) = 90^\circ - \tan^{-1} \left(\frac{\omega \omega_0 / Q}{\omega_0^2 - \omega^2} \right)$$

$$\text{Now } \frac{\partial}{\partial x} \tan^{-1} u = \frac{1}{1+u^2} \cdot \frac{\partial u}{\partial x}$$

$$\begin{aligned} \therefore \frac{\partial \phi}{\partial \omega} &= \frac{1}{1 + \left(\frac{\omega \omega_0 / Q}{\omega_0^2 - \omega^2} \right)^2} \cdot \frac{\partial}{\partial \omega} \left(\frac{\omega \omega_0 / Q}{\omega_0^2 - \omega^2} \right) \\ &= \frac{-(\omega_0^2 - \omega^2)^2}{(\omega_0^2 - \omega^2)^2 + \left(\frac{\omega \omega_0}{Q} \right)^2} \cdot \left[\frac{\frac{\omega_0}{Q} (\omega_0^2 - \omega^2) - 2\omega \frac{\omega \omega_0}{Q}}{(\omega_0^2 - \omega^2)^2} \right] \end{aligned}$$

$$\begin{aligned} \left. \frac{\partial \phi}{\partial \omega} \right|_{\omega=\omega_0} &= \frac{-1}{\omega_0^4 / Q^2} \cdot \frac{2\omega_0^2}{Q} \\ &= \underline{\underline{-\frac{2Q}{\omega_0}}} \end{aligned}$$

$$\begin{aligned} (c) \quad \Delta \omega_0 &= \frac{\Delta \phi}{\partial \phi / \partial \omega} = \frac{\Delta \phi}{-2Q / \omega_0} \\ &= \underline{\underline{-\frac{\Delta \phi \omega_0}{2Q}}} \end{aligned}$$

\therefore Per unit change in ω_0 is given by

$$\underline{\underline{\frac{\Delta \omega_0}{\omega_0} = -\frac{\Delta \phi}{2Q}}}$$

13.2

For the circuit of problem 13.1, the poles, which are the zeros of the characteristic equation, are given by:

$$1 - L(s) = 0$$

$$L(s) = 1$$

$$\frac{A k \left(\frac{\omega_0}{Q} \right) s}{s^2 + s \frac{\omega_0}{Q} + \omega_0^2} = 1$$

$$s^2 + s \frac{\omega_0}{Q} (1 - AK) + \omega_0^2 = 0$$

\therefore Poles are at:

$$s = \frac{-\frac{\omega_0}{Q} (1 - AK) \pm \sqrt{\left(\frac{\omega_0}{Q} \right)^2 (1 - AK)^2 - 4\omega_0^2}}{2}$$

$$= -\omega_0 \left[\frac{1 - AK}{2Q} \pm \sqrt{\left(\frac{1 - AK}{2Q} \right)^2 - 1} \right]$$

$$= -\omega_0 \left(\frac{1 - AK}{2Q} \right) \left[1 \pm j \sqrt{\left(\frac{2Q}{1 - AK} \right)^2 - 1} \right]$$

CONT.

Radial distance of $\omega_0 \Rightarrow$

$$|s^2| = \omega_0^2 \left(\frac{1-AK}{2Q} \right)^2 \left[1 + \left(\frac{2Q}{1-AK} \right)^2 - 1 \right]$$

$$= \omega_0^2$$

$\therefore |s| = \omega_0 \sim \text{independent of } K!$

(a) For poles on $j\omega$ -axis $\Rightarrow \text{real part} = 0$

$$\therefore -(1-AK) = 0 \Rightarrow \underline{AK=1}$$

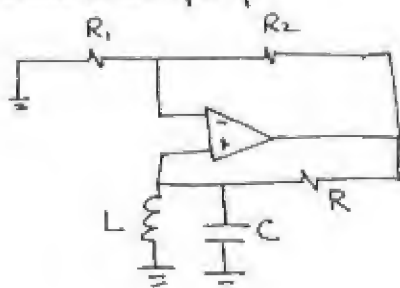
(b) For poles in RHS $\Rightarrow \text{RealPart} > 0$

$$-(1-AK) > 0$$

$$\underline{AK > 1}$$

13.3

Assume ideal opamp.



At resonance $\omega_0 = \frac{1}{\sqrt{LC}}$

$$K = 1$$

Thus A must also be 1 (or slightly higher).

For $R_1 = 10k\Omega$, $R_2 = 100\Omega$

$$A = 1 + \frac{R_2}{R_1} = \underline{1.01}$$

(a) If $L' = 1.01L$

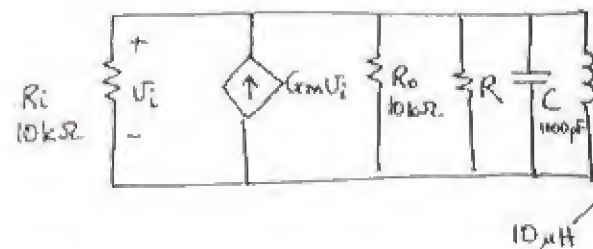
$$\omega_0' = \frac{1}{\sqrt{1.01}} \omega_0 = 0.995\omega_0$$

$$\text{or } \underline{-\frac{1}{2}\%}$$

(b) If C changes by +1%
 $\Rightarrow \omega_0$ changes by $\underline{-\frac{1}{2}\%}$

(c) If R changes by +1%
 $\Rightarrow \omega_0 \sim \underline{\text{unchanged}}$

13.4



For resonator: $\omega_0 = \frac{1}{\sqrt{LC}} = \underline{10^7 \frac{\text{rad}}{\text{s}}}$

$$\frac{\omega_0}{Q} = \frac{1}{RC}$$

$$R = \frac{Q}{\omega_0 C} = \frac{100}{10^7 \times 1000 \times 10^{-12}} = 10k\Omega$$

Oscillations will occur at $\omega_0 = 10^7 \frac{\text{rad}}{\text{s}}$

when $G_m(R_i \parallel R_o \parallel R) = 1$ i.e. gain = 1

$$\therefore G_m = \frac{1}{10k \parallel 10k \parallel 10k} = \frac{3}{10^4} = \underline{300 \frac{\mu\text{A}}{\text{V}}}$$

13.5

At ω_0 $A\beta = 1$

If $\beta(\omega_0)$ is -20dB with a phase

CONT.

shift of 180° then clearly A should have a gain of 20dB
(i.e. $A(\omega_0) = 10$) with a phase shift of $\pm 180^\circ$
i.e. $A = -10$

13.6

From Eq (13.8)

$$L_- = -V \frac{R_3}{R_2} - V_D \left(1 + \frac{R_3}{R_2}\right)$$

$$6 = 10 \frac{R_3}{R_2} + 0.7 \left(1 + \frac{R_3}{R_2}\right)$$

$$= 10.7 \frac{R_3}{R_2} + 0.7$$

$$\frac{R_3}{R_2} = 0.495 \quad \text{By symmetry } \frac{R_4}{R_5} = 0.495$$

Use $R_2 = R_5 = 10k\Omega$

$$\therefore \underline{R_3 = R_4 \approx 5k\Omega}$$

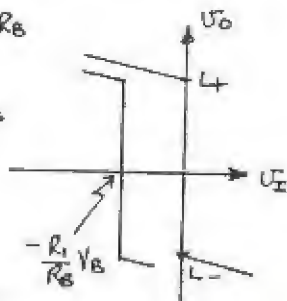
Slope of limiting characteristic

$$= \frac{R_4}{R_5} = 0.1$$

$$\therefore R_1 = \frac{1}{0.1} R_4 = \underline{50k\Omega}$$

13.7

For V_B connected via R_B to the virtual ground, a current $= \frac{V_B}{R_B}$ flows into the node. To compensate, V_I must be moved by ΔV_I , in a direction opposite to V_B to produce a current \Rightarrow



$$\frac{\Delta V_I}{R_1} = -\frac{V_B}{R_B}$$

$$\therefore \Delta V_I = -\frac{R_1}{R_B} V_B$$

$V_D = 0 \sim$ assumed

$$L_- = -5 = -15 \frac{R_3}{R_2}$$

$$\frac{R_3}{R_2} = \frac{1}{3} = \frac{R_4}{R_5}$$

Given $R_{in} = 100k\Omega \Rightarrow R_1 = \underline{100k\Omega}$

$$\text{Slope} = \frac{R_4}{R_1} \leq 0.05$$

$$R_4 \leq R_1 \times 0.05$$

$$R_4 \leq 5k\Omega \Rightarrow \text{let } \underline{R_4 = 4.3k\Omega}$$

$$\therefore R_3 = R_4 \Rightarrow$$

$$\underline{R_3 = 4.3k\Omega}$$

$$R_2 = R_5 = 3 R_4 = 12.9k\Omega$$

For standard resistance values:

$$R_2 = R_5 = \underline{13k\Omega}$$

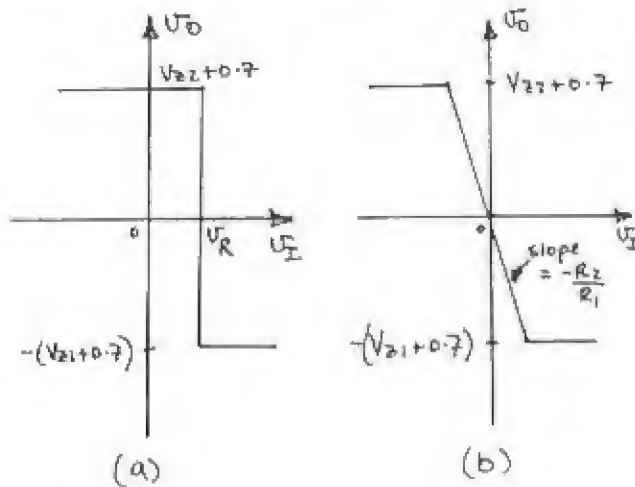
$$\therefore L_- = -15 \frac{R_3}{R_2} = -15 \times \frac{4.3}{12.9} = -4.96V \approx -5V$$

Offset is +5V \Rightarrow Use $V_B = -15V$

$$\text{and } 5 = \frac{R_1}{R_B} 15$$

$$\therefore R_B = 3 R_1 = \underline{300k\Omega}$$

13.8



$$\omega_0^2 = \frac{1}{R^2 C^2} \Rightarrow \omega_0 = \frac{1}{RC}$$

$$\frac{\omega_0}{Q} = \frac{3}{RC} \Rightarrow Q = \frac{1}{3}$$

For centre frequency gain:

$$s = j\omega_0 = j/RC$$

$$\therefore \left. \frac{V_o}{V_i} \right|_{s=j/RC} = \frac{\frac{1}{RC} \cdot j/RC}{-\frac{1}{R^2 C^2} + \frac{3}{RC} \left(\frac{j}{RC} \right) + \frac{1}{R^2 C^2}}$$

$$= \frac{1}{3} = \text{centre freq. gain}$$

13.9

$$\begin{aligned} \frac{V_o}{V_i} &= \frac{1/sC \parallel R}{1/sC \parallel R + 1/sC + R} \\ &= \frac{(1/sC)}{(1/sC + R)} \\ &= \frac{R}{\frac{R}{sC} + (1/sC + R)^2} \times \frac{s^2 C^2}{s^2 C^2} \\ &= \frac{SCR}{SCR + (1 + SCR)^2} \\ &= \frac{SCR}{SCR + 1 + 2SCR + S^2 C^2 R^2} \\ &= \frac{\frac{1}{RC} S}{S^2 + S \frac{2}{RC} + \frac{1}{R^2 C^2}} \end{aligned}$$

Note $\frac{V_o}{V_i}$ has zeros at 0 and ∞

i.e. A Bandpass!

13.10

$$L(j\omega) = \frac{1 + R_2/R_1}{3 + j(\omega CR - \frac{1}{\omega CR})} \quad \text{Eq(13.11)}$$

$$\phi(\omega) = -\tan^{-1} \left(\frac{\omega CR - \frac{1}{\omega CR}}{3} \right)$$

$$\text{using } \frac{\partial \tan^{-1} u}{\partial x} = \frac{1}{1+u^2} \frac{\partial u}{\partial x}$$

$$\frac{\partial \phi}{\partial \omega} = \frac{-1}{1 + \left(\frac{\omega CR - \frac{1}{\omega CR}}{3} \right)^2} \cdot \frac{1}{3} \left(CR + \frac{1}{\omega^2 CR} \right)$$

$$\left. \frac{\partial \phi}{\partial \omega} \right|_{\omega = \frac{1}{RC}} = \frac{-1}{3} \left(CR + CR \right) = -\frac{2}{3} CR$$

for $\Delta \phi = -0.1$ rad

$$\Delta \omega_0 = \frac{\Delta \phi}{\partial \phi / \partial \omega} = \frac{-0.1}{-2/3 \cdot \frac{1}{\omega_0}}$$

$$= 0.15 \omega_0$$

 \therefore New frequency of oscillation

$$= 1.15 \omega_0 = \frac{1.15}{RC}$$

13.11

Using Eq (13.10)

$$L(s) = \frac{1 + R_2/R_1}{3 + sCR + 1/sCR}$$

Poles of closed loop given by: $L(s) = 1$

$$1 + R_2/R_1 = 3 + sCR + \frac{1}{sCR}$$

$$0 = s^2 + \frac{s}{RC} \left(2 - \frac{R_2}{R_1} \right) + \frac{1}{R^2 C^2}$$

$$Q = \frac{1}{\left(2 - \frac{R_2}{R_1} \right)}$$

for $Q = \infty$ ~ poles on $j\omega$ axis
~ $R_2/R_1 = 2$

For poles in R.H.P. $R_2/R_1 > 2$

Using (2) $R_5 = 1k\Omega$

$$5 - \left(\frac{1}{1+R_6} \cdot (V_0 + 15) \right) - 0.7 = 1.65$$

$$\frac{20}{1+R_6} = 2.65$$

$$R_6 = \frac{20}{2.65} = 7.54$$

$$\underline{R_4 = 6.5k\Omega = R_3}$$

If $R_3 = R_6 = \infty$ from (2)

$$V_0 - \left(\frac{1}{1+\infty} (V_0 + 15) \right) - 0.7 = \frac{V_0}{3.03}$$

$$V_0 - 0.7 = \frac{V_0}{3.03}$$

$$V_0 = 1.04V$$

∴ output is $2V_0 = \underline{2.08V_{p-p}}$

13.12

From Fig (13.5) assuming resistance of limiting network is very low

At positive peak

$$V_0 = \left(1 + \frac{20.3k}{10k} \right) V_I = 3.03 V_I \quad (1)$$

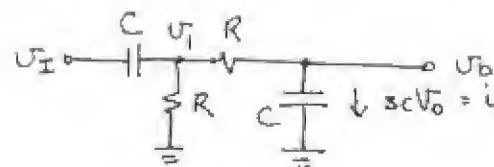
$$V_0 - \left[\frac{R_5}{R_5 + R_6} \cdot (V_0 - (-15)) \right] - 0.7 = V_I \quad (2)$$

Now for $10V_{p-p}$ out

$$\hat{V}_0 = 5V$$

$$\hat{V}_I = \frac{5}{3.03} = 1.65V$$

13.13



$$\frac{V_I - V_0}{R} = sC V_0 \Rightarrow V_I = V_0 (1 + sCR)$$

$\sum I$ at V_I

$$\frac{V_I}{R} + sC(V_I - V_I) + sC V_0 = 0$$

$$V_0(1 + sCR) + sCR(V_0 + V_0 sCR) - sCR V_I + sCR V_0 = 0$$

$$V_0(1 + sCR + sCR + s^2 C^2 R^2 + sCR) = sCR V_I$$

CONT.

$$\beta(s) \triangleq \frac{V_o}{V_i} = \frac{sCR}{s^2 C^2 R^2 + 3sCR + 1}$$

$$= \frac{1}{3 + sCR + \frac{1}{sCR}}$$

From Fig 13.8 $A = 1 + R_2/R_1$

$$\beta(j\omega) = \frac{1}{3 + j(\omega CR - \frac{1}{\omega CR})}$$

Zero phase when $\omega CR = \frac{1}{\omega CR}$

$$\omega = \frac{1}{CR}$$

$$|\beta(\omega = 1/RC)| = \frac{1}{3}$$

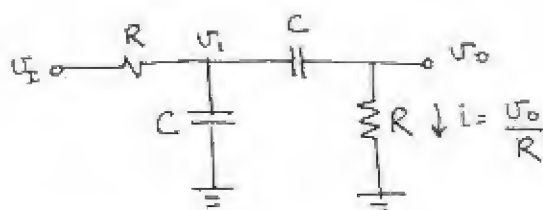
for oscillations $1 + R_2/R_1 \gg 3$

$$\Rightarrow \frac{R_2}{R_1} \gg 2$$

$$L(s) = A\beta = \frac{1 + R_2/R_1}{3 + sCR + \frac{1}{sCR}}$$

$$L(j\omega) = \frac{1 + R_2/R_1}{3 + j(\omega CR - \frac{1}{\omega CR})}$$

13.14



$$sC(V_1 - V_o) = \frac{V_o}{R}$$

$$V_1 = V_o \left(1 + \frac{1}{sCR} \right)$$

ΣI at V_1 :

$$\frac{-V_i + V_1}{R} + sC V_1 + \frac{V_o}{R} = 0 \quad \leftarrow \text{SUB FOR } V_1 \text{ and mult by } \frac{1}{sC}$$

$$\frac{1}{sCR} \left[-V_i + V_o \left(1 + sCR \right) \right] + V_o \left(1 + \frac{1}{sCR} \right) + \frac{V_o}{sCR} = 0$$

$$V_o \left[\frac{1}{sCR} + 1 + \frac{1}{sCR} + \frac{1}{s^2 C^2 R^2} + \frac{1}{sCR} \right] = \frac{V_i}{sCR}$$

$$\frac{V_o}{V_i} \triangleq \beta(s) = \frac{1}{3 + sCR + \frac{1}{sCR}}$$

$$\beta(j\omega) = \frac{1}{3 + j(\omega CR - \frac{1}{\omega CR})}$$

phase is zero when $\omega CR = \frac{1}{\omega CR}$

$$\omega_0 = \frac{1}{RC}$$

$$\beta(j\omega_0) = \frac{1}{3}$$

\therefore For oscillations

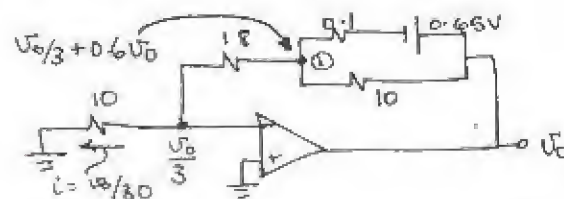
$$A = 1 + \frac{R_2}{R_1} \gg 3$$

$$\frac{R_2}{R_1} \gg 2$$

$$L(s) = \frac{1 + R_2/R_1}{3 + sCR + \frac{1}{sCR}}$$

$$L(j\omega) = \frac{1 + R_2/R_1}{3 + j(\omega CR - \frac{1}{\omega CR})}$$

13.15



CONT.

$\sum I$ at node ①

$$\frac{V_o}{30} = \frac{V_o - \frac{V_o}{3} - 0.6V_o}{10}$$

$$+ \frac{V_o - 0.65 - \frac{V_o}{3} - 0.6V_o}{0.1}$$

$$= 0.00666 V_o + 0.666 V_o - 0.65$$

$$V_o = 10.156 \text{ V}$$

$$\therefore \text{max. output} = \underline{20.3 \text{ V p-p}}$$

13.16

$$\omega_0 = \frac{1}{RC} = 2\pi \times 10^4 \quad R = 10 \text{ k}\Omega$$

$$C = \frac{1}{10^4 \times 2\pi \times 10^4} \Rightarrow \underline{C \approx 1.6 \text{ nF}}$$

Now from Eq (13.11)

$$\beta(j\omega) = \left[3 + j \left(\omega RC - \frac{1}{\omega RC} \right) \right]^{-1}$$

$$\therefore \phi(\omega) = -\tan^{-1} \left(\frac{\omega RC - \frac{1}{\omega RC}}{3} \right)$$

Using $\frac{\partial \tan^{-1} x}{\partial x} = \frac{1}{1+x^2} \frac{\partial x}{\partial x}$ we get

$$\frac{\partial \phi(\omega)}{\partial \omega} = \frac{-1}{1 + \left(\frac{\omega RC - \frac{1}{\omega RC}}{3} \right)^2} \left[\frac{RC + \frac{1}{\omega^2 RC}}{3} \right]$$

At $\omega = \omega_0 = \frac{1}{RC}$ $\frac{\partial \phi(\omega)}{\partial \omega} = -\frac{2}{3} RC$

Now $5.7^\circ \approx 0.1 \text{ rad}$ ($\text{lag} = -0.1 \text{ rad}$)

$$\therefore \Delta \omega_0 = \frac{-0.1}{-2/3 RC} = 0.15 \omega_0 = 1.5 \text{ kHz}$$

\therefore New frequency of oscillation = 8.5 kHz

To restore operation:



$$\beta(s) = \frac{R_x \parallel \frac{1}{sC}}{R_x \parallel \frac{1}{sC} + R + \frac{1}{sC}}$$

$$= \frac{R_x / sC}{R_x + 1/sC}$$

$$\frac{R_x / sC}{R_x + \frac{1}{sC}} + R + \frac{1}{sC}$$

$$= \frac{R_x / sC}{R_x / sC + R R_x + \frac{R}{sC} + \frac{R_x}{sC} + \frac{1}{s^2 C^2}}$$

$$\therefore \beta(s) = \frac{1}{2 + \frac{R}{R_x} + sC R + \frac{1}{sC R_x}}$$

$$\phi = \tan^{-1} \left(\frac{\omega RC - \frac{1}{\omega R_x C}}{2 + R/R_x} \right)$$

Now it is required that $\phi = 5.7^\circ$ at $\omega = \omega_0$ where $\omega_0 = 1/RC$

$$\therefore \omega_0 RC - \frac{1}{\omega_0 R_x C} = \left(2 + \frac{R}{R_x} \right) \tan(5.7^\circ)$$

$$1 - \frac{1}{\omega_0 R_x C} = \left(2 + \frac{R}{R_x} \right) (-0.1)$$

$$1 + 0.2 = \frac{1}{\omega_0 R_x C} - 0.1 \frac{R}{R_x}$$

CONT.

$$R_x = \frac{1/\omega_0 C - 0.1R}{1.2}$$

given:
 $\omega_0 = 2\pi \times 10^4$
 $C = 1.6 \times 10^{-9}$
 $R = 10^4$

$$R_x = \underline{7.5 k\Omega}$$

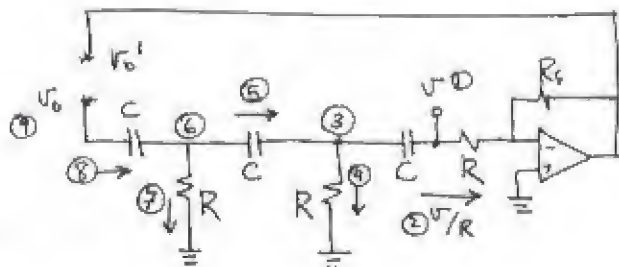
Now:

$$\begin{aligned} B(j\omega_0) &= \frac{1}{2 + j0.75 + j(1 - 1/\omega_0 C R)} \\ &= (3.333 - j0.326)^{-1} \end{aligned}$$

$$|B(j\omega_0)| = \frac{1}{3.35}$$

$\therefore 1 + R_2/R_1 = 3.35$ for oscillations
 $\frac{R_2}{R_1} = \underline{2.35}$ (not 2 as before)

13.17



$$(3) \quad V + \frac{1}{sC} \frac{V}{R} = V \left(1 + \frac{1}{sCR} \right)$$

$$(4) \quad \frac{V \left(1 + \frac{1}{sCR} \right)}{R} = \frac{V}{R} + \frac{V}{sCR^2}$$

$$(5) \quad i_s = \frac{2V}{R} + \frac{V}{sCR^2}$$

$$(6) \quad (3) + (5)/sC$$

$$= V + \frac{V}{sCR} + \frac{1}{sC} \left(2\frac{V}{R} + \frac{V}{sCR^2} \right)$$

$$= V + \frac{3V}{sCR} + \frac{V}{s^2 C^2 R^2}$$

$$(7) \quad \frac{V}{R} + \frac{3V}{sCR^2} + \frac{V}{s^2 C^2 R^3}$$

$$(8) = (5) + (7)$$

$$= \frac{3V}{R} + \frac{4V}{sCR^2} + \frac{V}{s^2 C^2 R^3}$$

$$(9) \quad V_0 = (6) + \frac{1}{sC} (8)$$

$$= V + \frac{3V}{sCR} + \frac{V}{s^2 C^2 R^2} + \frac{3V}{sCR} + \frac{4V}{s^2 C^2 R^2} + \frac{V}{s^3 C^3 R^3}$$

$$= V + \frac{6V}{sCR} + \frac{5V}{s^2 C^2 R^2} + \frac{V}{s^3 C^3 R^3}$$

Now loop gain \equiv

$$L(s) = -\frac{V_0'}{V_0}$$

$$\therefore L(s) = \frac{R_f/R \cdot V}{V \left(1 + \frac{6}{sCR} + \frac{5}{s^2 C^2 R^2} + \frac{1}{s^3 C^3 R^3} \right)}$$

$$= \frac{s^3 R_f/R}{s^3 + \frac{6s^2}{RC} + \frac{5s}{C^2 R^2} + \frac{1}{C^3 R^3}}$$

$$L(j\omega) = \frac{-j\omega^3 R_f/R}{\frac{1}{C^3 R^3} - \frac{6\omega^2}{RC} + j \left(\frac{5\omega}{C^2 R^2} - \omega^3 \right)}$$

CONT.

$L(j\omega)$ is real if

$$\frac{6\omega_0^2}{RC} = \frac{1}{R^3C^3}$$

$$\omega_0 = \frac{1}{\sqrt{6}RC}$$

$$\begin{aligned} L(j\omega_0) &= \frac{\omega_0^2 R_f/R}{-\omega_0^2 + 5/R^2C^2} \\ &= \frac{R_f/R \omega_0^2}{-\omega_0^2 + 30\omega_0^2} \\ &= \frac{R_f/R}{29} \end{aligned}$$

Now Loop Gain = 1 if $R_f = 29R$

\therefore Minimum value for $R_f = 29R$

Given $C = 16\text{nF}$, $R = 10\text{k}\Omega$

$$\begin{aligned} f_0 &= \frac{1}{2\pi \sqrt{6} \cdot 16 \times 10^{-9} \cdot 10 \times 10^3} \\ &= \underline{406.1\text{Hz}} \end{aligned}$$

$$\text{or } f_0 = \frac{0.065}{RC}$$

$$\textcircled{3} I = sCV \quad \textcircled{4} sCV + V/R$$

$$\textcircled{5} V + (sCV + \frac{V}{R})R = 2V + sCRV$$

$$\textcircled{6} 2sCV + s^2C^2RV$$

$$\textcircled{7} = \textcircled{6} + \textcircled{4} = 3sCV + s^2C^2RV + V/R$$

$$\begin{aligned} \textcircled{8} 2V + sCRV + V + 3sCRV + s^2C^2R^2V \\ = 3V + 4sCRV + s^2C^2R^2V \end{aligned}$$

$$\textcircled{9} 3sCV + 4s^2C^2RV + s^3C^3R^2V$$

$$\begin{aligned} \textcircled{10} &= \textcircled{7} + \textcircled{9} \\ &= 6sCV + 5s^2C^2RV + \frac{V}{R} + s^3C^3R^2V \end{aligned}$$

$$\textcircled{11} = \textcircled{8} + \textcircled{10} \times R$$

$$V_0 = 4V + 10sCRV + 6s^2C^2R^2V + s^3C^3R^3V$$

Now:

$$\begin{aligned} L(s) &= -\frac{V_0'}{V_0} = \frac{V R_f/R}{V(s^3C^3R^3 + 6s^2C^2R^2 + 10sCR + 4)} \\ &= \frac{R_f/R}{s^3C^3R^3 + 6s^2C^2R^2 + 10sCR + 4} \end{aligned}$$

$$L(j\omega) = \frac{R_f/R}{(4 - 6\omega^2C^2R^2) + j(10\omega CR + \omega^3R^3C^3)}$$

$L(j\omega)$ is purely real if

$$10\omega_0 CR = \omega_0^3 R^3 C^3$$

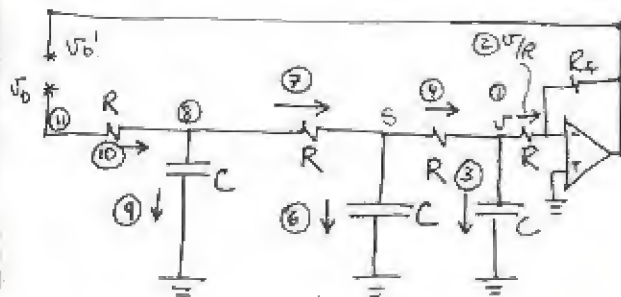
$$\omega_0 = \frac{1}{\sqrt{10}} \frac{1}{RC}$$

Given $R = 10\text{k}\Omega$, $f_0 = 10\text{kHz}$

$$\begin{aligned} C &= \frac{1}{\sqrt{10} \times 10^4 \times 2\pi \times 10^4} \\ &= \underline{0.503\text{nF}} \end{aligned}$$

CONT.

13-18



Now,
 $|L(j\omega_0)| = \frac{R_f/R}{4 - 6\omega_0^2 R^2 C^2}$ Sub for ω_0

$$= \frac{R_f/R}{4 - 6 \frac{1}{10R^2 C^2} R^2 C^2}$$

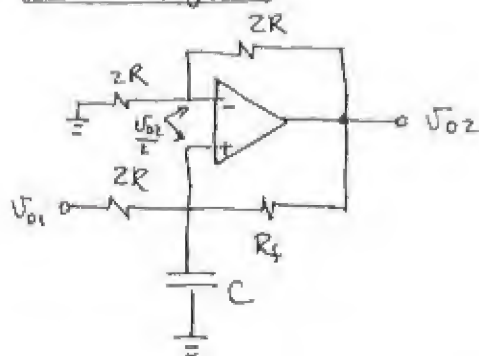
$$= \frac{R_f/R}{4 - 6/10} \gg 1$$

$$\therefore R_f/R \gg 3.4$$

$$\underline{\underline{R_f \gg 34 k\Omega}}$$

13.19

for 2nd integrator



From the voltage divider around the upper branch: $V_+ = V_- = \frac{1}{2} V_{o2}$

$\sum I = 0$ at +ve input

$$\frac{\frac{1}{2} V_{o2} - V_{o1}}{2R} + sC \frac{V_{o2}}{2} + \frac{V_{o2}}{2} - \frac{V_{o2}}{R_f} = 0$$

$$\frac{V_{o2} - 2V_{o1}}{2R} + sC \frac{V_{o2}}{2} - \frac{V_{o2}}{R_f} = 0 \quad R_f = \frac{2R}{1+\Delta}$$

$$V_{o2} \left(\frac{1}{2R} + sC - \frac{1+\Delta}{2R} \right) = \frac{V_{o1}}{R}$$

$$V_{o2} \left(sCR - \frac{\Delta}{2} \right) = V_{o1}$$

$$\therefore \frac{V_{o2}}{V_{o1}} = \frac{1}{sCR - \Delta/2}$$

Now: $\frac{V_{o1}}{V_x} = \frac{-1}{sCR} \therefore L(s) = \frac{-1/sCR}{sCR - \Delta/2}$

Characteristic equation $L(s) = 1$

$$\therefore s^2 C^2 R^2 - \frac{sCR\Delta}{2} + 1 = 0$$

\therefore Poles are

$$s_p = \frac{R\Delta/2}{2R^2 C^2} \pm \sqrt{\frac{R^2 C^2 \Delta^2}{4} - 4C^2 R^2}$$

$$= \frac{\Delta/2 \pm 2j \sqrt{1 - (\Delta/4)^2}}{2RC}$$

for $\Delta \ll 1$ $(1 - (\Delta/4)^2)^{1/2} \approx (1 - \frac{1}{2}(\Delta/4)^2)$

$$\therefore s_p \approx \left[\frac{\Delta/2 \pm j2(1 - \frac{1}{2}(\Delta/4)^2)}{2RC} \right] \frac{1}{2RC}$$

$$= \frac{\Delta/2 \pm j(2 - (\Delta/4)^2)}{2RC}$$

Now:

$$\text{Re}[s_p] > 0 \Rightarrow \text{Poles in R.H.P.}!$$

for $\Delta \ll 1$

$$s_p \approx \frac{\Delta/2 \pm j2}{2RC} = \frac{1}{RC} \left(\frac{\Delta}{4} \pm j \right)$$

Q.E.D.

13.20

The transmission of the filter normalized to the centre frequency, ω_0 is:

$$|T(j\omega)| = \frac{\omega\omega_0/Q}{(\omega_0^2 - \omega^2)^2 + \frac{\omega^2\omega_0^2}{Q^2}}$$

$$= \frac{\frac{1}{Q} \left(\frac{\omega_0}{\omega}\right)}{\left(\left(\frac{\omega_0}{\omega}\right)^2 - 1\right)^2 + \frac{1}{Q^2} \left(\frac{\omega_0}{\omega}\right)^2}$$

Relative to the amplitude of the fundamental

(a) The second harmonic = 0

(b) The third harmonic

$$= \frac{1}{3} \frac{\frac{1}{20} \times \frac{1}{3}}{\left(\frac{1}{9} - 1\right)^2 + \left(\frac{1}{20}\right)^2 \left(\frac{1}{9}\right)} = 6.25 \times 10^{-3}$$

(c) The fifth harmonic

$$= \frac{1}{5} \frac{\frac{1}{20} \times \frac{1}{5}}{\left(\frac{1}{25} - 1\right)^2 + \left(\frac{1}{20}\right)^2 \left(\frac{1}{25}\right)} = 2.08 \times 10^{-3}$$

(d) The 4th harmonic = 6th = 10th = 0

7th harmonic = 1.04×10^{-3}

9th " = 0.625×10^{-3}

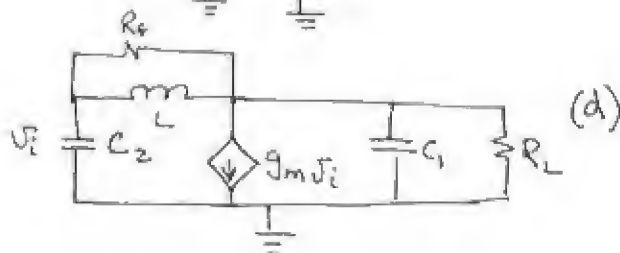
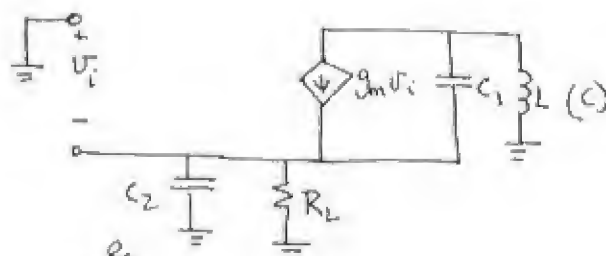
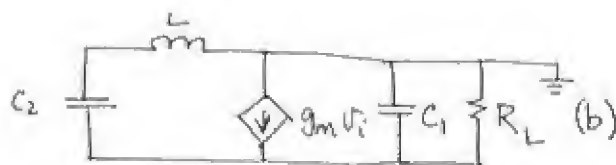
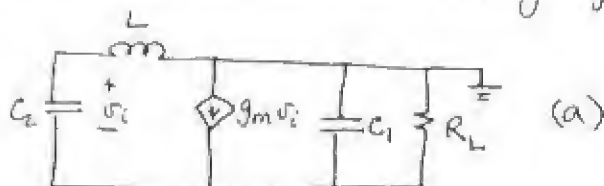
\therefore RMS of 2nd to 10th harmonic is
RMS of fundamental

$$\left[6.25^2 + 2.08^2 + 1.04^2 + 0.625^2\right]^{1/2} \times 10^{-3}$$

$$= \underline{6.7 \times 10^{-3}} \text{ OR } \underline{0.7\%}$$

13.21

Consider the small signal models for each circuit. Assume R_f very large:



Given $R_f \gg \omega_0 L$, circuits (a), (b) and (d) are the same except for the reference (ground) node.

For circuits (a), (b) & (d)



Break the loop at V_i and assume unit return.

CONT.

$$V_a = 1 + sC_2sL \\ = 1 + s^2C_2L$$

$$\Sigma I = 0 \text{ at } V_a$$

$$g_m + sC_2 + sC_1(1 + s^2C_2L) + \frac{(1 + s^2C_2L)}{R} = 0$$

$$\therefore g_m + \frac{1}{R} + s(C_1 + C_2) + \frac{s^2C_2L}{R} + \frac{s^2C_1C_2L}{R} = 0$$

This is the characteristic equation.
For $s = j\omega$:

$$g_m + \frac{1}{R} - \frac{\omega^2 C_2 L}{R} + j((C_1 + C_2)\omega - \omega^3 C_1 C_2 L) = 0$$

IMAGINARY PART = 0:

$$C_1 + C_2 = \omega^2 C_1 C_2 L \\ \omega = \sqrt{\frac{C_1 + C_2}{C_1 C_2 L}} \equiv \text{Frequency of Oscillation}$$

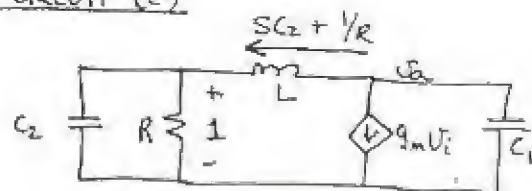
REAL PART = 0

$$g_m + \frac{1}{R} = \frac{\omega^2 C_2 L}{R}$$

$$g_m R = \left(\frac{C_1 + C_2}{C_1 C_2 L} \right) C_2 L - 1$$

$$g_m R = \frac{C_2}{C_1} \equiv \text{LIMIT ON GAIN}$$

FOR CIRCUIT (c)



$$V_a = (sC_2 + \frac{1}{R})sL + 1$$

$$\Sigma I = 0 \text{ at } V_a, V_i = 1$$

$$g_m + sC_2 + \frac{1}{R} + sC_1 \left[sL(sC_2 + \frac{1}{R}) + 1 \right] = 0$$

$$g_m + \frac{1}{R} + sC_2 + s^3 C_1 C_2 L + \frac{s^2 C_1 L}{R} + sC_1 = 0$$

THE CHARACTERISTIC EQUATION \equiv

$$g_m + \frac{1}{R} + s(C_1 + C_2) + \frac{s^2 C_1 L}{R} + s^3 C_1 C_2 L = 0$$

Note this is the same as above,
with $C_1 \leftrightarrow C_2$

$$\therefore \omega_0 = \sqrt{\frac{C_1 + C_2}{C_1 C_2 L}} \text{ and } g_m R = \frac{C_1}{C_2}$$

13.22

(a) Frequency of oscillations $\omega_0 = \frac{1}{\sqrt{LC}}$

$$\text{gain} \gg 1 \quad \text{gain} = \frac{R_c}{2r_e} = \frac{R_c}{2V_T/I} \\ = \frac{I R_c}{4V_T}$$

for $V_T = 0.026V$ then

$$I R_c \gg 4 V_T$$

$$R_c \gg 0.1/I \text{ for oscillations to start.}$$

(b) for $R_c = \frac{1}{I}$ (k Ω) we have

$$\text{gain} = \frac{1/I}{2(\frac{2V_T}{I})} = \frac{1}{4 \times 0.025} = 10$$

CONT.

Oscillations will start ($10 > 1$) and grow until Q_1, Q_2 , go into cutoff. Out put will go from V_{cc} to $V_{cc} - IR_c = V_{cc} - 1$. Therefore, output will be $1V_{p-p}$. Fundamental has a p-p amplitude of $\frac{4}{\pi} = 1.27 V_{p-p}$.

13.23

From Exercise B.10,

$$L = 0.52 H$$

$$C_s = 0.012 \mu F$$

$$C_p = 4 \mu F$$

From (B.27)

$$C_{eq} = \frac{C_s \left(C_p + \frac{C_1 C_2}{C_1 + C_2} \right)}{C_s + C_p + \frac{C_1 C_2}{C_1 + C_2}}$$

$$C_2 = 10 \mu F \quad C_1 = 1 \text{ to } 10 \mu F$$

$$C_L = \frac{0.012 \left(4 + \frac{10 \times 1}{10 + 1} \right)}{\left(0.012 + 4 + \frac{10}{11} \right)} = 0.01197 \mu F$$

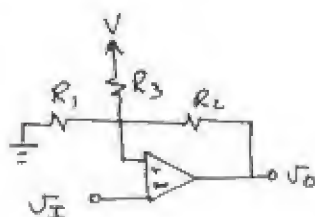
$$C_H = \frac{0.012 \left(4 + \frac{10 \times 10}{10 + 10} \right)}{\left(0.012 + 4 + \frac{100}{20} \right)} = 0.01198 \mu F$$

$$\therefore f_{OH} = \frac{1}{2\pi \left[0.52 \times 0.01197 \times 10^{-12} \right]^{1/2}} = 2.0172 \text{ MHz}$$

$$f_{OL} = \left[2\pi \left(0.52 \times 0.01198 \times 10^{-12} \right)^{1/2} \right]^{-1} = 2.01612 \text{ MHz}$$

$$\text{Difference} = 1 \text{ kHz!}$$

13.24



$\sum I$ at +ve node:

$$\frac{V_{TH}}{R_1} = \frac{V - V_{TH}}{R_3} + \frac{V - V_{TH}}{R_2}$$

$$V_{TH} \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \right) = \frac{V}{R_3} + \frac{V}{R_2}$$

$$V_{TH} = \left(\frac{V}{R_3} + \frac{V}{R_2} \right) \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \right)^{-1} = \left(\frac{V}{R_3} + \frac{V}{R_2} \right) R_1 \parallel R_2 \parallel R_3$$

Similarly

$$V_{TL} = \left(\frac{V}{R_3} - \frac{V}{R_2} \right) \left(R_1 \parallel R_2 \parallel R_3 \right)$$

(b) Now

$$V_{TH} = 5.1 = \left(\frac{15}{R_3} + \frac{13}{R_2} \right) \left(\frac{1}{10} + \frac{1}{R_2} + \frac{1}{R_3} \right)^{-1}$$

$$\frac{5.1}{10} + \frac{5.1}{R_2} + \frac{5.1}{R_3} = \frac{15}{R_3} + \frac{13}{R_2}$$

$$0.51 = \frac{7.9}{R_2} + \frac{9.9}{R_3} \quad (1)$$

AND

$$V_{TL} = 4.9 = \left(\frac{15}{R_3} - \frac{13}{R_2} \right) \left(\frac{1}{10} + \frac{1}{R_2} + \frac{1}{R_3} \right)^{-1}$$

$$0.49 = \frac{-17.9}{R_2} + \frac{10.1}{R_3} \quad (2)$$

$$(1) \times \frac{10.1}{9.9} \Rightarrow 0.52 = \frac{8.06}{R_2} + \frac{10.1}{R_3}$$

$$(2) \Rightarrow 0.49 = \frac{-17.9}{R_2} + \frac{10.1}{R_3} \quad \left. \begin{array}{l} \text{SUB-} \\ \text{TRACT} \\ \text{TO} \\ \text{GET} \\ \downarrow \end{array} \right\}$$

CONT.

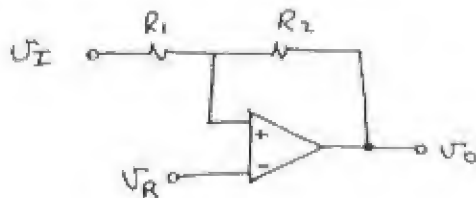
$$0.52 - 0.49 = \frac{8.06 + 17.9}{R_2}$$

$$R_2 = \frac{28.96}{0.0303} = \underline{\underline{856.8 \text{ k}\Omega}}$$

$$\frac{10.1}{R_3} = 0.49 + \frac{17.9}{856.8}$$

$$R_3 \cong \underline{\underline{19.8 \text{ k}\Omega}}$$

13.25



for $V_I = V_{TL}$ and $V_O = L+$ initially

$$\frac{L+ - V_R}{R_2} = \frac{V_R - V_{TL}}{R_1}$$

$$V_{TL} = V_R - \frac{R_1}{R_2} V_R - \frac{R_1}{R_2} L+$$

$$\therefore \underline{\underline{V_{TL} = V_R \left(1 - \frac{R_1}{R_2}\right) - \frac{R_1}{R_2} L+}}$$

Similarly

$$\frac{L- - V_R}{R_2} = \frac{V_R - V_{TH}}{R_1}$$

$$\underline{\underline{V_{TH} = V_R \left(1 + \frac{R_2}{R_1}\right) - \frac{R_1}{R_2} L-}}$$

(b) Given $L+ = -L- = V$
 $R_1 = 10 \text{ k}\Omega$
 $V_{TL} = 0$
 $V_{TH} = V/10$

Substituting these values we get:

$$0 = V_R \left(1 + \frac{10}{R_2}\right) - \frac{10}{R_2} V \quad (1)$$

$$\frac{V}{10} = V_R \left(1 + \frac{10}{R_2}\right) + \frac{10}{R_2} V \quad (2)$$

$$(1) - (2) \quad -\frac{V}{10} = -\frac{20}{R_2} V$$

$$R_2 = \underline{\underline{200 \text{ k}\Omega}}$$

$$0 = V_R \left(1 + \frac{10}{200}\right) - \frac{10}{200} V$$

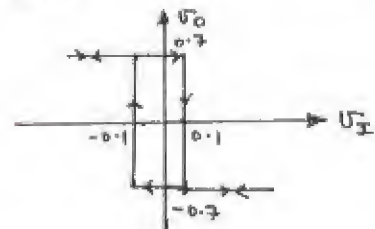
$$V_R = \frac{10/200 V}{1 + 10/200} = \underline{\underline{47.62 \text{ mV}}}$$

13.26

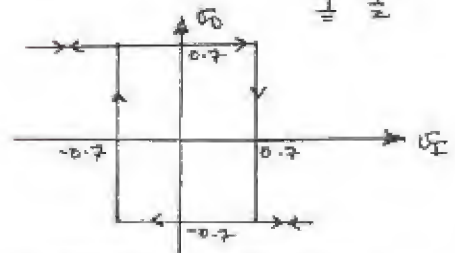
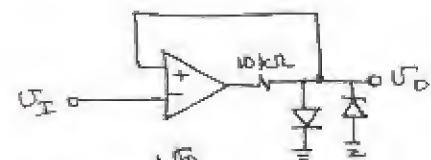
Output levels = $\pm 0.7 \text{ V}$

Threshold levels = $\pm \frac{10}{10+60} \times 0.7 = 0.1 \text{ V}$

$$i_{D, \max} = \frac{12 - 0.7}{10} = \frac{0.7}{10+60} = \underline{\underline{1.12 \text{ mA}}}$$



13.27



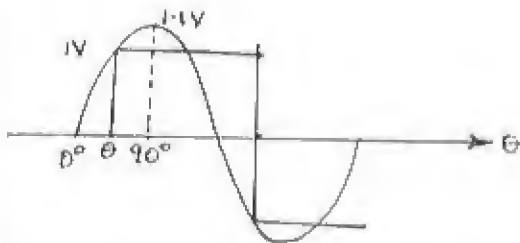
13.28

(a) A 0.5V peak sine wave, is not large enough to change the state of the circuit. Hence, the output will be either +12V or -12V at DC.

(b) The 1.1V peak will change the state when

$$1.1 \sin \theta = 1$$

$$\theta = 65.4^\circ$$



\therefore The output is a symmetric square wave at frequency f , and lags the sine wave by an angle of 65.4° . The square wave has a swing of $\pm 12V$.

Since $V_{TH} = -V_{TL} = 1V$, if the average shifts by an amount so either the +ve or -ve swing is $< 1V$, then no change of state will occur. Clearly, if the shift is 0.1V, the output will be a DC voltage.

13.29

$$\text{For } V_{TH} = -V_{TL} = 7.5V$$

$$V_Z = 6.8V \text{ with } V_D = 0.7V.$$

$$\text{For } V_{TH} = -V_{TL} = 7.5V \Rightarrow R_1 = R_2$$

$$\text{for } V_Z = 0 \quad I_{R_2} = 0.1mA = \frac{7.5}{R_1 + R_2}$$

$$\Rightarrow R_1 = R_2 = \underline{\underline{37.5 k\Omega}}$$

$$I_D = 1mA = \frac{12 - 7.5}{R} - \frac{7.5}{2R_1}$$

$$1 = \frac{4.5}{R} + 0.1$$

$$R = \underline{\underline{4.1 k\Omega}}$$

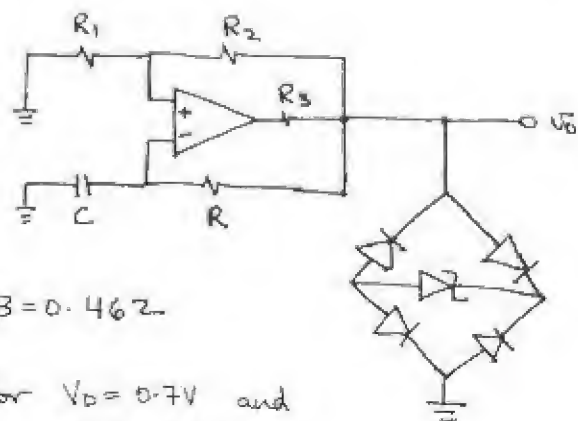
13.30

$$T = 2\tau \ln \frac{1+\beta}{1-\beta} \quad \beta = \frac{R_1}{R_1 + R_2} = \frac{10}{26}$$

$$T = 2(10 \times 10^{-9})(6.2 \times 10^3) \ln \left(\frac{1 + 10/26}{1 - 10/26} \right)$$

$$T = 1.006ms \Rightarrow f = \underline{\underline{994.5 Hz}}$$

13.31



$$\beta = 0.462$$

$$\text{For } V_D = 0.7V \text{ and}$$

$$V_O = \pm 5V$$

$$V_Z = 5 - 2V_D$$

$$V_Z = \underline{\underline{3.6V}}$$

CONT.

$$T = 2\tau \ln \left(\frac{1+B}{1-B} \right)$$

$$10^{-3} = 2\tau \ln \left(\frac{1.462}{1-0.462} \right) \Rightarrow \tau = 0.5 \text{ msec}$$

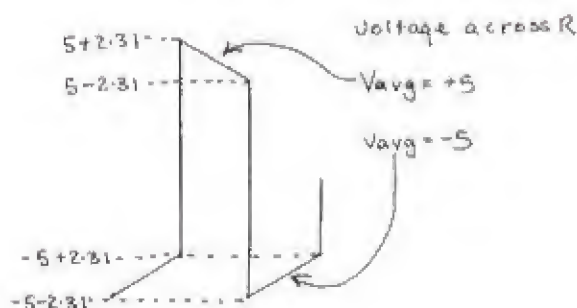
$$\tau = RC \Rightarrow R = \tau/C = \underline{50 \text{ k}\Omega}$$

$$\text{Thresholds} = \pm 0.462 \times 5 = \pm 2.31 \text{ V}$$

Average current in R in $\frac{1}{2}$ cycle:

$$I \approx \frac{1}{R} \left(\frac{5-2.31+2.31+5}{2} \right)$$

$$= \frac{5}{R} = \frac{5}{50 \text{ k}} = \underline{0.1 \text{ mA}}$$



$$R_1 + R_2 = \frac{5 \text{ V}}{0.1 \text{ mA}} = 50 \text{ k}\Omega$$

$$\frac{R_1}{R_1 + R_2} = 0.462 \rightarrow R_1 = 50(0.462)$$

$$= 23.1 \text{ k}\Omega$$

$$I = \frac{13-5}{R_3} = 0.1-0.1 \quad \therefore R_2 = 26.9 \text{ k}\Omega$$

$$= I_{\text{Diode}} \quad \text{use } \underline{R_1 = 23 \text{ k}\Omega}$$

$$\underline{R_2 = 27 \text{ k}\Omega}$$

$$R_3 = \frac{8}{1.2}$$

$$= \underline{6.67 \text{ k}\Omega}$$

13.32

From Fig 13.23(b), for $\pm 5 \text{ V}$ outputs
 $V_Z = 5 - 2V_{\text{Diode}} = 5 - 1.4 = \underline{3.6 \text{ V}}$

For $\pm 5 \text{ V}$ out:

$$R_1 = R_2 \quad L_+ = -L_- = 5 \text{ V}$$

$$V_{TH} = -V_{TH} = 5 \text{ V}$$

Max current in feedback network = 0.2 mA

$$\therefore 0.2 = \frac{5}{R_1 + R_2} \Rightarrow \underline{R_1 = R_2 = 25 \text{ k}\Omega}$$

Max diode current = 1 mA

$$\therefore \frac{13-5}{R_2} = (0.2+1) \text{ mA}$$

$$R_2 = \frac{8}{1.2} = \underline{6.67 \text{ k}\Omega}$$

Now from Fig 13.25(c)

$$\text{slope} = \frac{-L_-}{RC} = \frac{V_{TH} - V_{TL}}{T/2} \quad \text{for } f = 1 \text{ kHz}$$

$$T = 10^{-3} \text{ s}$$

$$C = 0.01 \mu\text{F}$$

$$\frac{5}{RC} = \frac{10}{10^{-3}/2} \Rightarrow \underline{R = 25 \text{ k}\Omega}$$

13.33

For 15 Vpp output $V_Z = 15/2 - 0.7$
 $= \underline{6.8 \text{ V}}$

For the integrator:



i.e. V_o should ramp between V_{TH} & V_{TL} !

CONT.

$$V_c(t_1) = \frac{1}{RC} \int_{t_0}^{t_1} V dt + V_c(t_0) \quad - V \text{ is a square wave}$$

$$\frac{7.5}{2} = \frac{1}{RC} (t_1 - t_0) (7.5 - (-7.5)) = \frac{7.5}{2}$$

$$(t_1 - t_0) = \frac{T}{2}$$

$$7.5 = \frac{1}{RC} \frac{T}{2} (15)$$

$$1 = \frac{T}{RC} \Rightarrow R = \frac{T}{C} = \frac{1}{fC}$$

$$= \frac{1}{10^4 (0.5 \times 10^{-9})}$$

$$\therefore R = R_{1-w} = 200 \text{ k}\Omega$$

Minimum zener current = 1mA

$$\frac{13 - 7.5}{R_p} = 1 + \frac{7.5}{R_1 + R_2} + \frac{7.5 - V_c}{R_3}$$

Maximum current into the integrator when $V_c = -\frac{7.5}{2}$

$$\therefore \frac{5.5}{7.5} = 1 + \frac{7.5}{400} + \frac{11.25}{200}$$

$$\therefore R_3 = 5.12 \text{ k}\Omega \xrightarrow{\text{use}} \underline{R_3 = 5.1 \text{ k}\Omega}$$

Integrator output is triangular, with period = 100 μ s and ± 7.5 V peaks. (i.e. 2x voltage at capacitor)

Trigger:

V_B :

V_A :
 $V_A = -(L_+ - L_-) e^{-t/RC}$

V_O :

13.35

For recovery, V_B goes from βL_- to L_+ until D_1 conducts at $V_{D1} = 0.7$ V

V_B :

For recovery

$$V_B = -0.1(12) + (12 + 0.1)(1 - e^{-t/\tau})$$

$$= 12 - 13.2 e^{-t/\tau}$$

At T_{recovery} :

$$V_{D1} = 12 - 13.2 e^{-T_r/\tau} \quad \tau = R_3 C_1$$

$$T_r = -R_3 C_1 \ln \left(\frac{V_{D1} - 12}{13.2} \right)$$

$$= -(6171) (0.1 \times 10^{-6}) \ln \left(\frac{11.3}{13.2} \right)$$

$$= \underline{96 \mu\text{s}}$$

13.34

See sketches that follow:

$$V_A(t=T) = -V_{\text{ref}} = -(L_+ - L_-) e^{-T/RC}$$

$$\frac{V_{\text{ref}}}{L_+ - L_-} = e^{-T/RC}$$

$$T = -RC \ln \left(\frac{V_{\text{ref}}}{L_+ - L_-} \right) = RC \ln \left(\frac{L_+ - L_-}{V_{\text{ref}}} \right)$$

Q.E.D.

13.36

choose $C_1 = 1 \text{ nF}$ $C_2 = 0.1 \text{ nF}$

$$R_1 = R_2 = 100 \text{ k}\Omega \Rightarrow \beta \approx \frac{1}{2}$$

$$T \approx C_1 R_3 \ln \left(\frac{0.7 + 13}{-13(0.5 - 1)} \right)$$

$$10^{-4} = 10^{-9} R_3 \ln \left(\frac{13.7}{13(0.5)} \right)$$

$$R_3 = 134.1 \text{ k}\Omega$$

Need $R_4 \gg R_1 \Rightarrow$ choose $R_4 = 470 \text{ k}\Omega$

$$\begin{aligned} \text{Min trigger voltage} &= \beta V_L - V_{O2} + V_{O1} \\ &= \underline{6.5 \text{ V}} \end{aligned}$$

For recovery

$$\begin{aligned} V_B &= 13 - (13 - \beta V_L) e^{-t/\tau} \\ &= 13 - 14.5 e^{-t/\tau} = 0.7 \end{aligned}$$

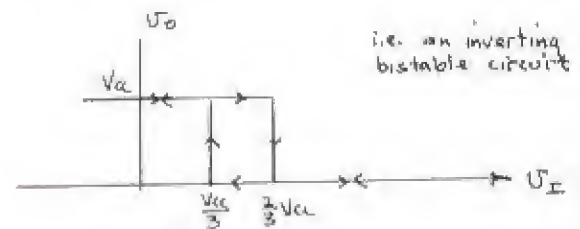
$$\therefore t_{\text{recovery}} = -\tau \ln \left(\frac{12.3}{14.5} \right)$$

$$\begin{aligned} &= (134.1 \times 10^3)(10^{-9})(-0.4608) \\ &= \underline{61.8 \mu\text{s}} \end{aligned}$$

13.37

For $V_I > \frac{2}{3} V_{CC}$ comp-1 = "1" and comp-2 = "0" and flip flop is reset. I.E. $V_O = 0 \text{ V}$. Now V_O will not change until $V_I = \frac{1}{3} V_{CC}$, when comp-2 = "1" and comp-1 = "0" and FF is set: I.E. $V_O = V_{CC}$

For $\frac{1}{3} V_{CC} < V_I < \frac{2}{3} V_{CC}$, comp-1 = comp-2 = "0" and no change of state will occur.



13.38

$$(a) \quad C = 1 \text{ nF} \quad V_C = V_{CC}(1 - e^{-t/\tau}) \quad \text{where } \tau = RC$$

Pulse width of $10 \mu\text{s}$ when $V_C = V_{TH} = \frac{2}{3} V_{CC}$

$$\therefore \frac{2}{3} = 1 - e^{-t/RC} \quad t = T = 10 \mu\text{s}$$

$$\begin{aligned} -\frac{T}{RC} &= \ln \left(\frac{1}{3} \right) \Rightarrow R = \frac{-T}{C \ln(1/3)} \\ &= \underline{9.1 \text{ k}\Omega} \end{aligned}$$

$$(b) \quad \text{for } T = 20 \mu\text{s} \quad R = 9.1 \text{ k}\Omega, C = 1 \text{ nF}$$

$$\begin{aligned} \therefore V_{TH} &= 15(1 - e^{-T/RC}) \\ &= 15 \left(1 - e^{-\frac{20 \times 10^{-6}}{9.1 \times 10^3 \times 10^{-9}}} \right) \\ &= \underline{13.3 \text{ V}} \end{aligned}$$

13.39

$$C = 680 \text{ pF} \quad f = 50 \text{ kHz}$$

$$T = 20 \mu\text{s} = T_H + T_L$$

$$\begin{aligned} \text{For } 75\% \text{ Duty} \quad T_H &= 15 \mu\text{s} \\ T_L &= 5 \mu\text{s} \end{aligned}$$

From Eq (13.43) we have:

CONT.

$$T_L = CR_B \ln 2$$

$$\therefore R_B = \frac{5 \times 10^{-6}}{680 \times 10^{-12} \ln(2)} = \underline{\underline{10.6 \text{ k}\Omega}}$$

From Eq (13.41)

$$T_H = C(R_A + R_B) \ln(2)$$

$$R_A = \frac{15 \times 10^{-6}}{680 \times 10^{-12} \ln(2)} - 10.6 \times 10^3$$

$$= \underline{\underline{21.2 \text{ k}\Omega}}$$

$$\therefore T_H + T_L = T = \ln 2 (R_A + 2R_B) C$$

$$T = 9.98 \mu\text{s} \rightarrow \underline{\underline{f = 100 \text{ kHz}}}$$

$$\text{Duty cycle} = \frac{T_H}{T_H + T_L} = \frac{R_A + R_B}{R_A + 2R_B} = 0.75$$

$$\Rightarrow \underline{\underline{75\%}}$$

$$(c) V_{CC} = 5V, V_{TH} = \frac{2}{3} \times 5 = \frac{10}{3} = 3.33V$$

$$\text{for 1V input } V_{TH}' = 4.33V$$

$$V_{TL}' = \frac{1}{2} V_{TH}' = 2.17V$$

$$T_H' = 10^{-9} (3.6 + 7.2) \times 10^3 \ln \left(\frac{5 - 2.17}{5 - 4.33} \right)$$

$$= \underline{\underline{15.6 \mu\text{s}}}$$

$$T_L' = 10^{-9} \times 3.6 \times 10^3 \ln 2 = \underline{\underline{2.5 \mu\text{s}}}$$

$$\therefore f = \frac{1}{(15.6 + 2.5) \times 10^{-6}} = \underline{\underline{55.2 \text{ kHz}}}$$

$$\text{duty cycle} = \frac{15.6}{2.5 + 15.6} = \underline{\underline{86.2\%}}$$

$$\text{for 1V input } V_{TH}'' = 2.33$$

$$V_{TL}'' = 1.17$$

$$\therefore T_H'' = 10^{-9} (3.6 + 7.2) \times 10^3 \ln \left(\frac{5 - 1.17}{5 - 2.33} \right)$$

$$= \underline{\underline{3.92 \mu\text{s}}}$$

$$T_L'' + T_L' = 2.5 \mu\text{s}$$

$$\therefore f = \frac{10^6}{(3.92 + 2.5)} = \underline{\underline{156 \text{ kHz}}}$$

$$\text{duty cycle} = \frac{3.92}{2.5 + 3.92} = \underline{\underline{61\%}}$$

13.40



For the rise:

$$V_C = V_{CC} - (V_{CC} - V_{TL}) e^{-t/C(R_A + R_B)}$$

$$V_{TH} = V_{CC} - (V_{CC} - V_{TL}) e^{-T_H/C(R_A + R_B)}$$

$$\frac{V_{CC} - V_{TH}}{V_{CC} - V_{TL}} = e^{-T_H/C(R_A + R_B)}$$

$$\underline{\underline{T_H = C(R_A + R_B) \ln \left(\frac{V_{CC} - V_{TL}}{V_{CC} - V_{TH}} \right)}}$$

For exponential fall:

$$V_C = V_{TH} e^{-t/CR_B}$$

$$\therefore V_{TL} = V_{TH} e^{-T_L/CR_B}$$

$$T_L = CR_B \ln \left(\frac{V_{TH}}{V_{TL}} \right)$$

$$\text{for } V_{TH} = 2V_{TL} \Rightarrow T_L = CR_B \ln(2)$$

$$(b) C = 1nF, R_A = 7.2 \text{ k}\Omega, R_B = 3.6 \text{ k}\Omega$$

$$V_{CC} = 5V, V_{TH, sat} = 0$$

13.41

for sine wave: $V_0 = 0.7 \sin \omega t$

slope at zero crossing

$$0.7 \omega \cos \omega t \big|_{t=V_0}$$

$$= 0.7 \omega = 0.7 (2\pi f)$$

Slope of triangular wave with peak of V volts and period T is:

$$\frac{V - -V}{T/2} = \frac{2V}{\frac{T}{2}} = 4Vf$$

Equating the slopes:

$$4Vf = 0.7 (2\pi f)$$

$$V = 0.7 \times \frac{2\pi}{4} = \underline{\underline{1.0996}}$$

$$\text{Now } R = \frac{1.0996 - 0.7}{1 \text{ mA}} = 399.6 \Omega$$

$$\approx \underline{\underline{400 \Omega}}$$

V_0 changes by 0.1 V per decade change in current.

$$\therefore V_0 = 0.7 + 0.1 \log \left(\frac{I_x}{1 \text{ mA}} \right)$$

$$\Rightarrow I_x = 10^{\frac{V_0 - 0.7}{0.1}} \text{ mA}$$

For output of 0.7 V $I_x = 1 \text{ mA}$ and
 $\theta = 90^\circ$
 Error = 0%

$$\text{output} = 0.65 \text{ V } I_x = 0.316 \text{ mA}$$

$$\therefore V_E = 0.65 + 0.316 \times 0.4$$

$$= 0.7765 \text{ V}$$

$$\theta = \frac{0.7765}{1.0996} \times 90^\circ = 63.6^\circ$$

$$\text{output} = 0.6 \text{ V } I_x = 0.1 \text{ mA}$$

$$V_E = 0.6 + 0.1 \times 0.4 = 0.640 \text{ V}$$

$$\theta = \frac{0.640}{1.0996} \times 90^\circ = 52.4^\circ$$

$$\text{out} = 0.55 \text{ V } I_x = 0.0316 \text{ mA}$$

$$V_E = 0.55 + 0.0316 \times 0.4$$

$$= 0.563 \text{ V}$$

$$\theta = \frac{0.563}{1.0996} \times 90^\circ = 46.1^\circ$$

$$\text{out} = 0.5 \text{ V } I_x = 0.01 \text{ mA}$$

$$V_E = 0.5 + 0.01 \times 0.4 = 0.504 \text{ V}$$

$$\theta = \frac{0.504}{1.0996} \times 90^\circ = 41.3^\circ$$

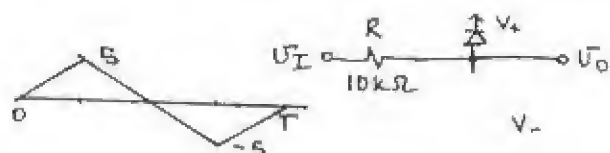
OUT (V)

0.4	32.8°
0.3	24.6°
0.2	16.4°
0.1	8.2°
0	0°

Summarizing in Table Form:

V_0 (V)	θ	0.7 Sin θ	% Error
0.7	90	0.7	0
0.65	63.6	0.627	3.7
0.6	52.4	0.554	8.2
0.55	46.1	0.504	9.1
0.50	41.3	0.462	8.2
0.40	32.8	0.379	5.5
0.30	24.6	0.291	3.0
0.20	16.4	0.198	1.2
0.10	8.2	0.0998	0.1
0.00	0	0.0	0.0

13.42



$$v_O = A \sin \frac{2\pi}{T} t$$

Slope of v_O at $t=0$,

$$\frac{dv_O}{dt} = A \frac{2\pi}{T} \cos\left(\frac{2\pi}{T} t\right) \Big|_{t=0}$$

$$= \frac{A 2\pi}{T} \equiv \text{SLOPE AT ZERO CROSSING}$$

$$\text{Slope of } \Delta\text{-wave} = \frac{5}{T/4} = \frac{20}{T}$$

$$\therefore \frac{20}{T} = \frac{A 2\pi}{T}$$

$$A = 3.18V$$

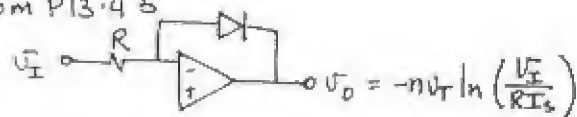
\therefore Clamp voltage:

$$V_+ = -V_- = 3.18 - 0.7$$

$$= 2.48 = \underline{\underline{2.5V}}$$

13.44

from P13.43



Now,

$$V_A = -nV_T \ln \frac{V_1}{RI_S}$$

$$R = 1k\Omega$$

$$V_B = -nV_T \ln \frac{V_2}{RI_S}$$

$$V_1, V_2 > 0$$

$$V_C = +nV_T \ln \frac{1}{RI_S}$$

$$V_D = -(V_A + V_B + V_C)$$

$$= nV_T \left(\ln \left[\frac{V_1}{RI_S} \times \frac{V_2}{RI_S} \times \frac{RI_S}{1} \right] \right)$$

$$= nV_T \ln \left(\frac{V_1 V_2}{RI_S} \right)$$

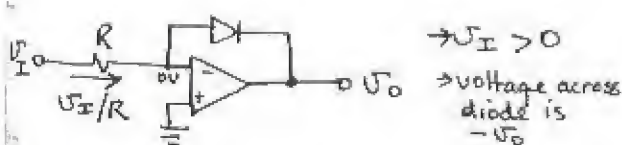
$$i_{D4} = I_S e^{V_D/nV_T}$$

$$= I_S \times \frac{V_1 V_2}{RI_S} = \frac{V_1 V_2}{R}$$

$$V_D = -i_{D4} R = -\frac{V_1 V_2}{R} \times R$$

$$\therefore \underline{\underline{V_D = -V_1 V_2}} \quad \text{ANALOG MULTIPLIER}$$

13.43



$\rightarrow v_I > 0$

\rightarrow voltage across diode is $-v_O$

$$i_D = \frac{v_I}{R} = I_S e^{-v_O/nV_T}$$

$$-\frac{v_O}{nV_T} = \ln \left(\frac{v_I}{RI_S} \right)$$

$$v_O = -nV_T \ln \left(\frac{v_I}{RI_S} \right), \quad v_I > 0$$

Q.E.D.

To check $v_1 = 0.5, v_2 = 2$

$$I_{D1} = 0.5mA \rightarrow V_A = -0.7 + nV_T \ln \left(\frac{0.5}{1} \right)$$

$$= -0.7 + 2(0.025) \ln \left(\frac{1}{2} \right)$$

$$= -0.6653V$$

$$I_{D2} = 2mA \rightarrow V_B = (0.7 + 0.05 \ln(2))(1)$$

$$= -0.7347V$$

$$I_{D3} = 1mA \rightarrow V_C = 0.700V$$

$$V_D = -(0.6653 - 0.7347 + 0.7) = 0.7V$$

CONT.

$$V_D = V_{D4} = 0.7V \Rightarrow I_{D4} = 1mA$$

$$\therefore V_0 = -1V \quad \text{i.e. } 2 \times 0.5 = 1$$

$$\text{For } V_1 = 3, \quad V_2 = 2:$$

$$I_{D1} = 3mA \rightarrow V_A = -(0.7 + 0.05 \ln 3) = -0.7549V$$

$$I_{D2} = 2mA \rightarrow V_B = -(0.7 + 0.05 \ln 2) = -0.7347V$$

$$I_{D3} = 1mA \rightarrow V_C = 0.7V$$

$$\therefore V_D = V_{D4} = -(V_A + V_B + V_C) = +0.7896V$$

$$\therefore \frac{I_{D4}}{1mA} = \frac{I_{D1} e^{V_D/0.05}}{I_{D1} e^{0.7/0.05}}$$

$$I_{D4} = e^{\frac{0.7896 - 0.7}{0.05}} = 6mA$$

$$\therefore V_0 = -6V \quad \text{i.e. } 2 \times 3 = 6$$

$$\text{For squarer: } V_1 = 2 \text{ through } \frac{1}{2} k\Omega \text{ resistor}$$

$$I_{D1} = 4mA \rightarrow V_A = -(0.7 + 0.05 \ln 4) = -0.7693$$

$$V_D = -(-0.7693) = 0.7693V$$

$$I_{D4} = e^{\frac{0.7693 - 0.7}{0.05}} = 3.999mA$$

$$\therefore V_0 = -3.999V \quad \text{i.e. } 2^2 = 4$$

13.45

$$\text{Say } V_{BE} = \tilde{V}_D @ I \quad n=1$$

$$\text{for } V_0 = 0.25 V_T:$$

$$I_R = \frac{0.25 V_T}{R} = \frac{0.25 V_T}{\frac{2.5 V_T}{I}} = \frac{I}{10}$$

$$V_{BE1} = \tilde{V}_D + nV_T \ln \left(\frac{I + I/10}{I} \right) \approx \tilde{V}_D + V_T \ln(1.1)$$

$$V_{BE2} = \tilde{V}_D + nV_T \ln \left(\frac{I - I/10}{I} \right) \approx \tilde{V}_D + V_T \ln(0.9)$$

$$V_I = -V_{BE2} + V_0 + V_{BE1}$$

$$= V_T [\ln(1.1) + 0.25 - \ln(0.9)]$$

$$= \underline{0.451 V_T}$$

$$\text{For } V_0 = 0.5 V_T$$

$$I_R = \frac{0.5 I}{2.5} = 0.2 I$$

$$V_I = V_T [\ln(1.2) + 0.5 - \ln(0.8)]$$

$$= \underline{0.905 V_T}$$

$$V_0 = V_T \quad I_R = 0.4 I$$

$$V_I = V_T [\ln 1.4 + 1 - \ln 0.6]$$

$$= \underline{1.847 V_T}$$

$$V_0 = 1.5 V_T \quad I_R = 0.6 I$$

$$V_I = V_T [\ln 1.6 + 1.5 - \ln 0.4]$$

$$= \underline{2.886 V_T}$$

$$V_0 = 2 V_T \quad I_R = 0.8 I$$

$$V_I = V_T (\ln 1.8 + 2 - \ln 0.2) = \underline{4.197 V_T}$$

$$V_0 = 2.4 V_T \quad I_R = 0.96 I$$

$$V_I = V_T (\ln 1.96 + 2.4 - \ln 0.04) = \underline{6.292 V_T}$$

$$V_0 = 2.42 V_T \quad I_R = 0.968 I$$

$$V_I = V_T (\ln 1.968 + 2.42 - \ln 0.032)$$

$$= \underline{6.519 V_T}$$

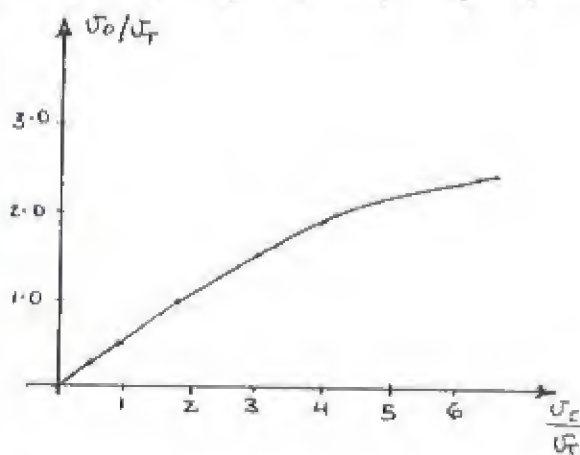
CONT.

Ideal curve given by

$$V_o = 2.42 V_T \sin\left(\frac{V_I}{6.6 V_T} \times 90^\circ\right)$$

$$\frac{V_I}{V_T} = \frac{6.6}{90} \sin^{-1}\left(\frac{V_o}{2.42 V_T}\right)$$

V_o/V_T	0.25	0.50	1.00	1.50	2.00	2.40	2.42
V_I/V_T	0.451	0.905	1.85	2.89	4.20	6.29	6.52
V_I/V_T (ideal)	0.435	0.874	1.79	2.81	4.09	6.06	6.60



for $V_I > 0$

$$V_o = V_I - \frac{0.7}{A}$$

$$\approx V_I$$

with D_1 "on"

D_2 "off"

for $V_I < 0$

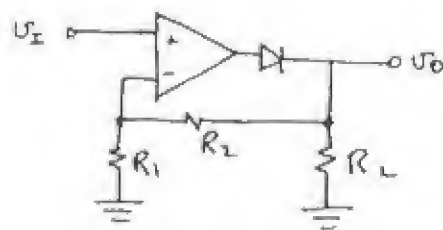
$$V_o = V_I + \frac{0.7}{A}$$

$$\approx V_I$$

with D_1 "off"

D_2 "on"

13.47

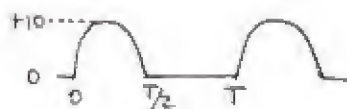


for $V_I \geq 0$

$$V_o = \left(1 + \frac{R_2}{R_1}\right) V_I$$

for a gain of 2 $R_1 = R_2 = 10k\Omega$

for $V_I = 10V_{pp}$ sine wave $V_o \Rightarrow$



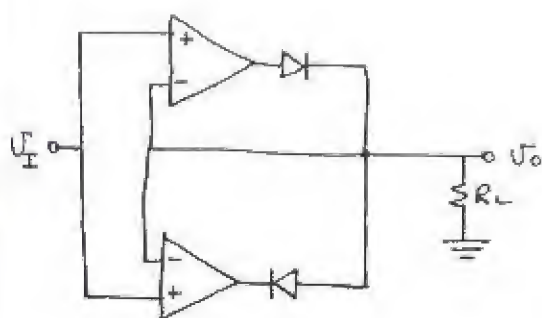
$$Avg = \frac{1}{T} \int_0^{T/2} 10 \sin \frac{2\pi}{T} t dt$$

$$= \frac{1}{T} \frac{T}{2\pi} \cos \frac{2\pi}{T} t \times (-10) \Big|_{t=0}^{T/2}$$

$$= \frac{-10}{2\pi} (\cos \pi - \cos 0)$$

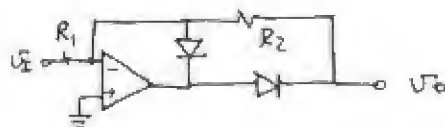
$$= 10/\pi = \underline{\underline{3.18V}}$$

13.48



for high opamp gain $V_o = V_I$

$\therefore V_o$ is also a $10V_{pp}$ sine wave.



CONT.

for $V_{\pm} < 0 \Rightarrow V_o = -R_2/R_1$

$$R_{in} = R_1 = 100k\Omega \quad \therefore R_2 = 200k\Omega$$

13.49

for high R_{in} , need $R_1 = 1M\Omega$

AC gain is given by R_2/R_1

$$\Rightarrow R_2 = 1M\Omega$$

Now for 1Vrms sine, peak is 1.414V.

The value of V_i is then $\frac{1.414}{\pi} = 0.450V$

For 10V out at second stage

$$\text{gain (dB)} = \frac{10}{0.450} = 22.2$$

$$\therefore R_4/R_3 = 22.2$$

$\frac{1}{2\pi R_4 C} = 10Hz$ (i.e. corner frequency)

To make C small, make $R_4 = 1M\Omega$

$$\therefore C = 15.9nF$$

$$R_3 = \frac{1M\Omega}{22.2} = 45k\Omega$$

13.50

At the two terminal $V_r = -5V$

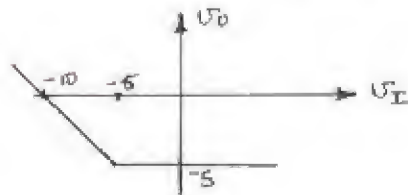
for $V_{\pm} > -5$ D_1 is "ON" and faces virtual short. $\therefore V_r = -5$, and no current will flow in feedback R.

$$\therefore V_o = -5V$$

for $V_{\pm} < -5$ - D_1 "off" and

$$\frac{V_o}{V_{\pm}} = \frac{-5 - V_{\pm}}{R} = \frac{V_o + 5}{R}$$

$$\Rightarrow V_o = -V_{\pm}$$



13.51

for $V_{\pm} < 0$

D_2 "off"

$$\frac{V_{o1}}{V_{\pm}} = -1$$

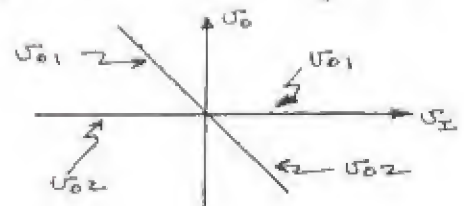
$$\frac{V_{o2}}{V_{\pm}} = 0$$

for $V_{\pm} > 0$

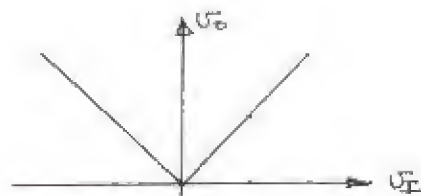
D_1 - "off"

$$\frac{V_{o1}}{V_{\pm}} = 0$$

$$\frac{V_{o2}}{V_{\pm}} = -1$$



13.52



For $V_{\pm} < 0$ - Diode is on, and cathode is forced to $\approx 0V$.

$$\therefore V_o/V_{\pm} = -1$$

For $V_{\pm} > 0$ - Diode is off, and the cathode now follows V_{\pm} since no current flows in Resistor. So V_o must follow

CONT.

V_{\pm} so that no current flows in feedback resistor.

$$\therefore \frac{V_o}{V_{\pm}} = +1$$

$$\frac{V}{10^3} |\sin 2\pi 60t| = 2\pi 60 VC |\cos 2\pi 60t|$$

$$\therefore C = \frac{1}{2\pi 60 \cdot 10^3} = \underline{\underline{2.65 \mu F}}$$

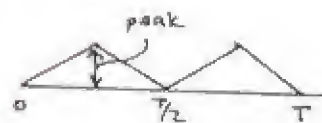
$$\text{At } 120\text{Hz: } i_m = 2\pi 120 VC |\cos 2\pi 60t|$$

$$i_{m,120} = 2 i_{m,60}$$

$$\text{At } 180\text{Hz: } i_{m,180} = 3 i_{m,60}$$

For D-wave

with R_i
 $i_m = 1\text{mA}$, $R = 1\text{k}\Omega$



\therefore Full wave rectified wave has average voltage = V . $\therefore V_{\text{peak}} = 2V$

$$\text{with } C: \text{ slope} = \frac{V_{\text{peak}}}{T/4} = 4V_{\text{peak}} f$$

$$= 4 \times 2 \times 60 = 480$$

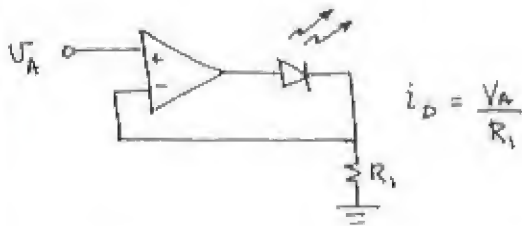
Now, current through the capacitor will be a square wave (50% duty cycle)

$$\text{Peak current} = 2.65 \times 10^{-6} \times 480 = 1.27 \text{ mA}$$

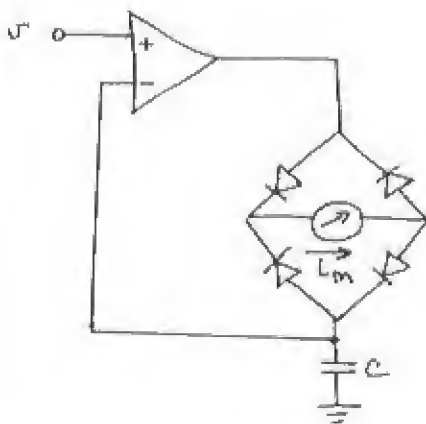
$$\therefore i_m = i_{\text{avg}} = \underline{\underline{1.27 \text{ mA}}}$$

13.53

Simply place the LED in the feedback path.



13.54



$$i_m = |i_c| = C \frac{dV}{dt} \quad \text{using } R = 1\text{k}\Omega$$

$$i_m = |i_r| = \frac{|V|}{R} = \frac{|V|}{1\text{k}\Omega} \Rightarrow i_m = |V| \text{ mA}$$

$$\text{Now } V = V \sin 2\pi 60t$$

$$\Rightarrow i_m = C \times 2\pi 60 |\cos (2\pi 60t)|$$

for equivalence:

13.55

10V pulses of $10\mu\text{s}$, and large C_{load} , will cause the op amp to current limit.

Charge transferred in one pulse:

$$Q = (10\text{mA})(10\mu\text{s})$$

$$= 10^{-7} \text{ C}$$

CONT

Voltage change per pulse:

$$\Delta V = Q/C = \frac{10^{-7}}{10 \times 10^{-6}} = 10 \text{ mV}$$

After: 1 pulse	$V_c = 10 \text{ mV}$
2 pulses	20 mV
10 pulses	100 mV

to reach 0.5 V	require 50 pulses
1.0 V	100 "
2.0 V	200 "

13.56

For $1V_{pp}$, peak detector output:
 $V_o = 0.5 \text{ V}$.

$$\text{Ripple Voltage} = (1\%) 0.5 = 5 \text{ mV}$$

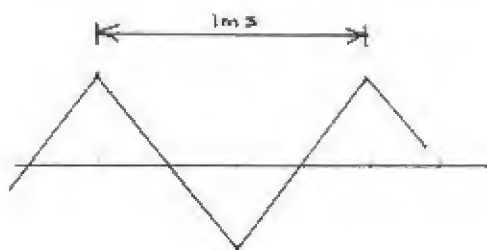
$$\text{Total leakage} = 10 + 1 = 11 \text{ nA}$$

\therefore total charge lost:

$$\Delta Q = 11 \text{ nA} \times 1 \text{ ms} = 11 \text{ pC}$$

\therefore Required capacitance:

$$C = \frac{Q}{\Delta V} = \frac{11 \times 10^{-12}}{5 \times 10^{-3}} = \underline{\underline{2.2 \text{ nF}}}$$



Chapter 14 - Problems

14

14.1 Refer to Fig. 14.2 (Page 1232). The upper limit of the output voltage is determined by the saturation of Q_1 , so

$$V_{Omax} = V_{CC} - V_{CEsat} \\ = 5 - 0.3 = 4.7 \text{ V}$$

The corresponding input is

$$V_I = 4.7 + 0.7 = 5.4 \text{ V}$$

The bias current I is

$$I = \frac{0 - (-V_{CC} + V_{BE2})}{R} \\ = \frac{5 - 0.7}{1} = 4.3 \text{ mA}$$

The lower limit of V_O is determined by either Q_1 cutting off,

$$\frac{-V_O}{R_L} = I \Rightarrow V_O = -4.3 \text{ V}$$

or by Q_2 saturating,

$$V_O = -V_{CC} + V_{CEsat} = -4.7 \text{ V}$$

Obviously, $V_{Omin} = -4.3 \text{ V}$

and the corresponding input is

$$V_I = -4.3 + 0.7 = -3.6 \text{ V}$$

If the emitter-base junction area of Q_2 is made twice as large as that of Q_1 , I becomes one half its previous value,

$$I = \frac{4.3}{2} = 2.15 \text{ mA}$$

and thus the lower limit of V_O changes to

$$V_{Omin} = -IR_L = -2.15 \text{ V}$$

The corresponding value of V_I is

$$V_I = -2.15 + 0.7 = -1.45 \text{ V}$$

The upper limit does not change.

14.2 First we determine the

bias current I as

follows:

$$I = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_t)^2$$

$$\text{But } V_{GS} = 5 - IR \\ = 5 - I$$

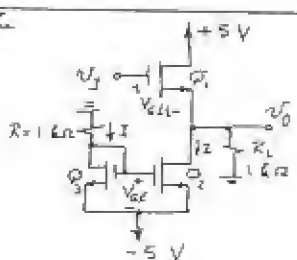
Then

$$I = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (5 - I - V_t)^2$$

$$I = 10 (5 - I - 1)^2$$

$$\Rightarrow I^2 - 8.4I + 16 = 0$$

$$I = 3.416 \text{ mA and } V_{GS} = 1.584 \text{ V}$$



The upper limit on V_O is determined by Q_1 , leaving the saturation region (and entering the triode region). This occurs when V_{I1} exceeds V_{DS1} by V_t volts,

$$V_{I1max} = 5 + 1 = 6 \text{ V}$$

To obtain the corresponding value of V_O we must find the corresponding value of V_{GS1} , as follows:

$$V_O = V_{I1} - V_{GS1}$$

$$I_1 = \frac{V_O}{R_L} = \frac{V_{I1} - V_{GS1}}{1}$$

$$= V_{I1} - V_{GS1} = 6 - V_{GS1}$$

$$I_1 = I + I_L$$

$$= 3.416 + 6 - V_{GS1}$$

$$= 9.416 - V_{GS1}$$

$$\text{But } I_1 = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_{GS1} - V_t)^2$$

$$\text{Thus, } 9.416 - V_{GS1} = 10 (V_{GS1} - 1)^2$$

$$\Rightarrow V_{GS1}^2 - 1.9 V_{GS1} + 0.0584 = 0$$

$$V_{GS1} = 1.869 \text{ V}$$

$$V_{Omax} = 6 - 1.869$$

$$= 4.131 \text{ V}$$

The lower limit of V_O is determined either by Q_1 cutting off,

$$V_O = -IR_L = -3.416 \times 1 = -3.416 \text{ V}$$

or by Q_2 leaving saturation,

$$V_O = V_{GS2} - V_t$$

$$= -5 + 1.584 - 1 = -4.416 \text{ V}$$

$$\text{Thus, } V_{Omin} = -3.416 \text{ V}$$

The corresponding value of V_I is determined by noting that since Q_1 is on the verge of cut-off, $V_{GS1} = V_t = 1 \text{ V}$ and

$$V_{I1} = -3.416 + 1 = -2.416 \text{ V}$$

14.3 Refer to Fig. 14.2. With $V_{CC} = +9 \text{ V}$, the upper limit on V_O is $+8.7 \text{ V}$, which is greater than the required value of $+7 \text{ V}$. To obtain a lower limit of -7 V we select I so that

$$IR_L = 7$$

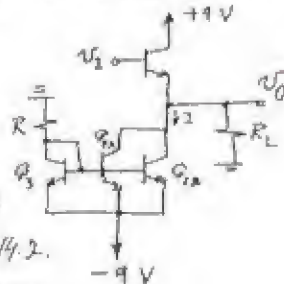
$$\Rightarrow I = 7 \text{ mA}$$

Since we are provided with four devices, we can minimize the total supply current by paralleling two devices to form Q_2 as shown below. The resulting supply current will be $3 \times \frac{I}{2}$ rather than $2I$ which is the value obtained in the circuit of Fig. 14.2.

Thus the supply current is 10.5 mA . The value of R is found from

$$R = \frac{8.3 \text{ V}}{3.5 \text{ mA}} = 2.37 \text{ k}\Omega$$

In a practical design, we would select a standard value for R that results in I somewhat larger than 7 mA . Say, $R = 2.2 \text{ k}\Omega$



144 Refer to Fig. 14.2. For a load resistance of 100Ω and V_0 ranging between -5 V and $+5 \text{ V}$, the maximum current through Q_1 is

$$I + \frac{5}{0.1} = I + 50, \text{ mA} \text{ and}$$

the minimum current is

$$I - \frac{5}{0.1} = I - 50, \text{ mA}.$$

For a current ratio of 10,

$$\frac{I + 50}{I - 50} = 10$$

$$\Rightarrow I = 61.1 \text{ mA}$$

$$R = \frac{9.3 \text{ V}}{61.1 \text{ mA}} = 152 \Omega$$

The incremental voltage gain is

$$A_v = \frac{R_L}{R_L + r_{e1}}$$

For $R_L = 100 \Omega$;

$$\text{At } V_0 = +5 \text{ V}, I_{E1} = 61.1 + 50 = 111.1 \text{ mA}$$

$$r_{e1} = \frac{25}{111.1} = 0.225 \Omega$$

$$A_v = \frac{100}{100 + 0.225} = 0.998 \text{ V/V}$$

$$\text{At } V_0 = 0 \text{ V}, I_{E1} = 61.1 \text{ mA}$$

$$r_{e1} = \frac{25}{61.1} = 0.409 \Omega$$

$$A_v = \frac{100}{100 + 0.409} = 0.996 \text{ V/V}$$

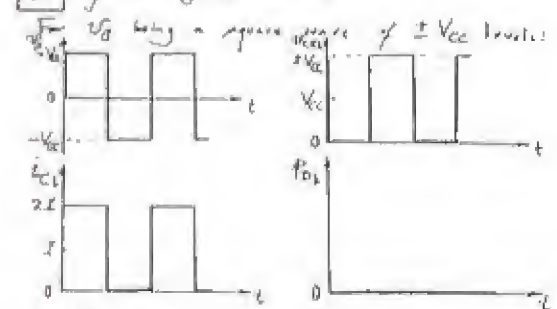
$$\text{At } V_0 = -5 \text{ V}, I_{E1} = 61.1 - 50 = 11.1 \text{ mA}$$

$$r_{e1} = \frac{25}{11.1} = 2.25 \Omega$$

$$A_v = \frac{100}{100 + 2.25} = 0.978 \text{ V/V}$$

Thus the incremental gain changes by $0.998 - 0.978 = 0.02$ or about 2% over the range of V_0 .

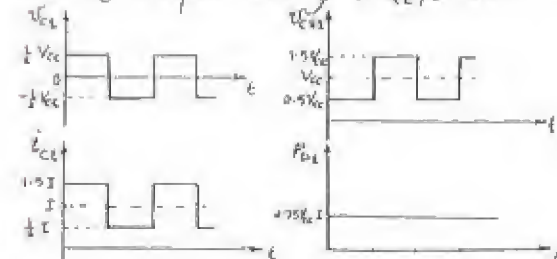
145 Refer to Fig. 14.2 and 14.4



$$P_{Di, \text{average}} = 0$$

For the corresponding sine-wave case [Fig. 14.4], P_{Di} is $\frac{1}{2} V_{CC} I$

For V_0 a square wave of $\pm V_{CC}/2$ levels:



$$P_{Di, \text{average}} = 0.75 V_{CC} I$$

For a sine-wave output of $V_{CC}/2$ peak amplitude,

$$V_{CE1} = \frac{1}{2} V_{CC} \sin \theta$$

$$i_{C1} = I + \frac{1}{2} \frac{V_{CC}}{R_L} \sin \theta = I + \frac{1}{2} I \sin \theta$$

$$V_{CE1} = V_{CC} - \frac{1}{2} V_{CC} \sin \theta$$

$$P_{Di} = (V_{CC} - \frac{1}{2} V_{CC} \sin \theta) (I + \frac{1}{2} I \sin \theta)$$

$$= V_{CC} I - \frac{1}{4} V_{CC} I \sin^2 \theta$$

$$= V_{CC} I - \frac{1}{4} V_{CC} I \times \frac{1}{2} (1 - \cos 2\theta)$$

$$= \frac{3}{8} V_{CC} I + \frac{1}{8} V_{CC} I \cos 2\theta$$

$$P_{Di, \text{average}} = \frac{3}{8} V_{CC} I$$

14.6 In all cases, the average voltage across Q_2 is equal to V_{CC} . Thus, since Q_2 conducts a constant current I , its average power dissipation is $V_{CC} I$.

14.7 $V_{CC} = 16, 12, 10$ and 8 V
 $I = 100$ mA $R_L = 100 \Omega$
 $\hat{V}_o = 8$ V
 $\eta = \frac{1}{4} \left(\frac{\hat{V}_o}{IR_L} \right) \left(\frac{\hat{V}_o}{V_{CC}} \right)$
 $= \frac{1}{4} \left(\frac{8}{10} \right) \left(\frac{8}{V_{CC}} \right) = \frac{1.6}{V_{CC}}$

V_{CC}	16	12	10	8
η	10%	13.3%	16%	20%

14.8 Refer to Fig. P14.8. The bias current I is

$$I = \frac{1}{2} I_{CQ1} (0 - (-2))^2 = 10 \times 4 = 40 \text{ mA}$$

For $R_L = \infty$, the maximum V_o is limited by the saturation of Q_1 to $V_{CC} - V_{CEsat} = 14.7$ V, and the minimum V_o is limited by Q_2 leaving Q_1 in the triode region to $-V_{CC} + |V_{BE}| = -3$ V.

For $R_L = 100 \Omega$, the maximum V_o is still 14.7 V, and the minimum V_o is still -3 V because at this level the current in R_L is 30 mA and thus Q_1 is still conducting 10 mA. (That is, the cut off limit of -40 mA $\times 100 \Omega = -4$ V is not applicable since Q_2 would have entered the triode region.)

To obtain a 1-V peak sine-wave output, R_L must be limited to (\leq)

$$R_L = \frac{1 \text{ V}}{40 \text{ mA}} = 25 \Omega$$

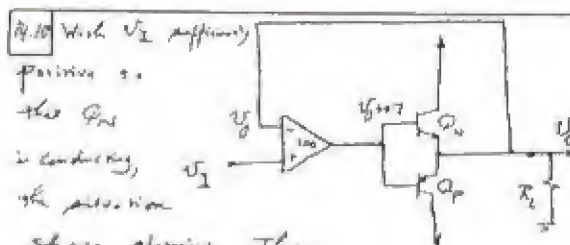
For this case,

$$\eta = \frac{1}{4} \left(\frac{\hat{V}_o}{IR_L} \right) \left(\frac{\hat{V}_o}{V_{CC}} \right)$$

$$= \frac{1}{4} \left(\frac{1}{0.04 \times 25} \right) \left(\frac{1}{5} \right)$$

$$= 5 \%$$

14.9 Refer to Figs. 14.6 and 14.7. A 10% loss in peak amplitude is obtained when the amplitude of the input signal is 5 V.



$$(V_I - V_O) \times 100 = V_O + 0.7$$

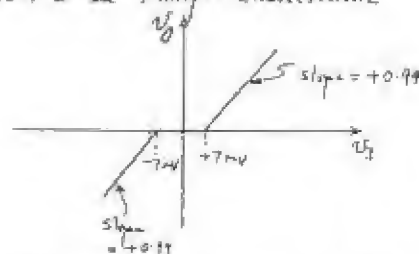
$$\Rightarrow V_O = \frac{1}{1.01} (V_I - 0.007)$$

The relationship applies for $V_I \geq 0.007$. Similarly, for V_I sufficiently negative so that Q_P conducts, the voltage at the output of the amplifier becomes $V_O - 0.7$, then

$$(V_I - V_O) \times 100 = V_O - 0.7$$

$$\Rightarrow V_O = \frac{1}{1.01} (V_I + 0.007)$$

The relationship applies for $V_I \leq -0.007$. The result is the transfer characteristic.

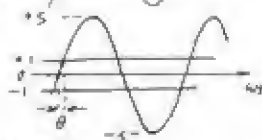


Without the feedback arrangement, the deadband becomes ± 700 mV and the slope change is little (to ± 1 V/V).

14.11 With $R_L = \infty$ and $V_I = +5\text{ V}$, v_O will be $V_I - V_{GS1} = V_I - V_t = 4\text{ V}$ (since the current is virtually zero and thus $V_{GS} \approx V_t$). Thus the resulting peak output voltage will be 4 V .

$\sin \theta = \frac{1}{5}$
 $\Rightarrow \theta = 11.34^\circ$

Cross-over interval = 4θ
 Fraction of cycle = $\frac{4\theta}{360^\circ} = 12.8\%$

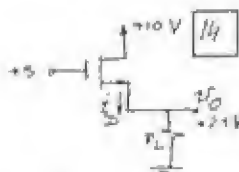


For $V_I = +5\text{ V}$ and $v_O = +2.5\text{ V}$, $V_{GS} = 2.5\text{ V}$, then

$$I_{D1} = K_n (V_{GS} - V_t)^2$$

$$= 0.1 (2.5 - 1)^2 = 0.225\text{ mA}$$

Then, $R_L = \frac{2.5}{0.225} = 11.1\text{ k}\Omega$



14.12 For $V_{CC} = 10\text{ V}$ and $R_L = 100\Omega$, the maximum time-average output power occurs when $\hat{V}_o = V_{CC}$ and

$$P_{Lmax} = \frac{1}{2} \frac{V_{CC}^2}{R_L}$$

$$= \frac{1}{2} \times \frac{100}{100} = 0.5\text{ W}$$

Correspondingly,

$$P_{S+} = P_{S-} = \frac{1}{\pi} \frac{\hat{V}_o}{R_L} V_{CC}$$

$$= \frac{1}{\pi} \times \frac{10}{100} \times 10 = 0.318\text{ W}$$

for a total supply power of

$$P_S = 2 \times 0.318 = 0.637\text{ W}$$

The power conversion efficiency η is

$$\eta = \frac{P_L}{P_S} \times 100 = \frac{0.5}{0.637} \times 100 = 78.5\%$$

For $\hat{V}_o = 5\text{ V}$,

$$P_L = \frac{1}{2} \frac{\hat{V}_o^2}{R_L} = \frac{1}{2} \times \frac{25}{100} = \frac{1}{8}\text{ W}$$

$$P_{S+} = P_{S-} = \frac{1}{\pi} \frac{\hat{V}_o}{R_L} V_{CC}$$

$$= \frac{1}{\pi} \times \frac{5}{100} \times 10 = \frac{1}{2\pi}\text{ W}$$

$$P_S = \frac{1}{\pi}\text{ W} = 0.318\text{ W}$$

$$\eta = \frac{1/8}{1/\pi} \times 100 = \frac{\pi}{8} \times 100 = 39.3\%$$

14.13 $V_{CC} = 5\text{ V}$

For maximum η ,

$$\hat{V}_o = V_{CC} = 5\text{ V}$$

The output voltage that results in maximum device dissipation is given by Eq. (9.20),

$$\hat{V}_o = \frac{2}{\pi} V_{CC}$$

$$= \frac{2}{\pi} \times 5 = 3.18\text{ V}$$

If operation is always at full output voltage, $\eta = 78.5\%$ and then

$$P_{\text{dissipation}} = (1 - \eta) P_S$$

$$= (1 - \eta) \frac{P_L}{\eta} = \frac{1 - 0.785}{0.785} P_L = 0.274 P_L$$

$$P_{\text{dissipation/device}} = \frac{1}{2} \times 0.274 P_L = 0.137 P_L$$

For a rated device dissipation of 1 W , and using a factor of 2 safety margin,

$$P_{\text{dissipation/device}} = 0.5\text{ W}$$

$$= 0.137 P_L$$

$$\Rightarrow P_L = 3.65\text{ W}$$

$$3.65 = \frac{1}{2} \times \frac{25}{R_L}$$

$$\Rightarrow R_L = 3.425\Omega \quad (\text{i.e. } R_L \geq 3.425\Omega)$$

The corresponding output power (i.e. greatest possible output power) is 3.65 W .

If operation is allowed at $\hat{V}_o = \frac{1}{2} V_{CC} = 2.5\text{ V}$,

$$\eta = \frac{\pi}{4} \frac{\hat{V}_o}{V_{CC}} \quad (\text{Eq. 9.15})$$

$$= \frac{\pi}{4} \times \frac{1}{2} = 0.393$$

$$P_{\text{dissipation/device}} = \frac{1}{2} \frac{1 - \eta}{\eta} P_L = 0.772 P_L$$

$$0.5 = 0.772 P_L$$

$$\Rightarrow P_L = 0.647\text{ W}$$

$$= \frac{1}{2} \frac{2.5^2}{R_L}$$

$$\Rightarrow R_L = 4.83\Omega \quad (\text{i.e. } \geq 4.83\Omega)$$

14.14 $P_L = \frac{1}{2} \frac{V_o^2}{R_L}$ 14

$$100 = \frac{1}{2} \frac{V_o^2}{16}$$

$$V_o = 56.6 \text{ V}$$

$$V_{CC} = 56.6 + 6 = 60.6 \rightarrow \underline{61 \text{ V}}$$

Peak current from each supply = $\frac{V_o}{R_L} = \frac{56.6}{16}$

$$P_{S+} = P_{S-} = \frac{1}{\pi} \times 3.54 \times 61 = \underline{3.54 \text{ A}}$$

Then, $P_S = \frac{2}{\pi} \times 3.54 \times 61$

$$= 137.4 \text{ W}$$

$$\eta = \frac{P_L}{P_S} = \frac{100}{137.4} = \underline{73 \%}$$

Using Eq. (9.22),

$$P_{D(max)} = P_{D(min)} = \frac{V_{CC}^2}{\pi^2 R_L} = \frac{61^2}{\pi^2 \times 16}$$

$$= \underline{23.6 \text{ W}}$$

14.15 $P_L = \frac{V_o^2}{R_L}$

$$P_{L1} = P_{L2} = \frac{1}{2} \left(\frac{V_o}{R_L} \right) V_{SS}$$

$$P_S = \frac{V_o}{R_L} V_{SS}$$

$$\eta = \frac{P_L}{P_S} = \frac{V_o^2 / R_L}{V_o V_{SS} / R_L} = \frac{V_o}{V_{SS}}$$

$\eta_{max} = 1$ (100%), obtained for $V_o = V_{SS}$

$P_{L(max)} = \frac{V_{SS}^2}{R_L}$ 14

$$P_{dissipation} = P_S - P_L$$

$$= \frac{V_o}{R_L} V_{SS} - \frac{V_o^2}{R_L}$$

$$\frac{dP_{dissipation}}{dV_o} = \frac{V_{SS}}{R_L} - \frac{2V_o}{R_L}$$

$$= 0 \text{ for } \underline{V_o = \frac{V_{SS}}{2}}$$

Correspondingly, $\eta = \frac{V_{SS}/2}{V_{SS}} = \frac{1}{2}$ or 50%

14.17 $R_{out} = \frac{1}{g_m} \parallel \frac{1}{g_m} = \frac{1}{2g_m} = 10 \Omega$ 14

$$\Rightarrow g_m = \frac{1}{20} = 50 \text{ mA/V}$$

But, $g_m = \mu C_{ox} \frac{W}{L} (V_{GS} - V_T)$

$$50 = 2 \times 100 (V_{GS} - 1)$$

$$\Rightarrow V_{GS} = 1.25 \text{ V}$$

$$V_{GG} = \underline{2.5 \text{ V}}$$

14.18 $I_D = 1 \text{ mA}$

For output of -1 V , $i_L = -\frac{1}{100} = -10 \text{ mA}$

Using Eq. (14.17),

$$i_N^2 - i_L i_N - I_D^2 = 0$$

$$i_N^2 + 10 i_N - 1 = 0$$

$$i_N = 0.1 \text{ mA}$$

$$i_P = \underline{10.1 \text{ mA}}$$

Then V_{DSQ} increases by V_T to $\frac{10.1}{1} = 10.1 \text{ V}$
 and the input step must be -1.06 V
 Largest possible positive output from 6 to 10, i.e. 4V.
 Largest negative output from 6 to 0, i.e. 6V

14.19 $R_{out} = r_e / 2 = 10 \Omega$ 14

$$\Rightarrow r_e = 20 \Omega$$

$$I_D = \frac{V_T}{r_e} = \frac{25}{20} = 1.25 \text{ mA}$$

Then, $m = \frac{1.25}{0.1} = \underline{12.5}$

14.16 $A_v = \frac{R_L}{R_L + R_{out}}$

where, $R_{out} = \frac{r_e}{2} = \frac{V_T}{2 I_D}$

For $A_v \geq 0.99$ with $R_L \geq 100 \Omega$,

$$0.99 = \frac{100}{100 + R_{out}} \Rightarrow R_{out} = 1 \Omega$$

$$\frac{V_T}{2 I_D} = 1 \Rightarrow I_D = \underline{12.5 \text{ mA}}$$

$$V_{BB} = 2 V_{BE}$$

$$= 2 \left[0.7 + V_T \ln \frac{12.5}{100} \right]$$

$$= \underline{1.296 \text{ V}}$$

1420 $I_Q \approx I_{bias} = 0.5 \text{ mA}$, neglecting the base current of Q_N . More precisely,

$$I_Q = I_{bias} - \frac{I_Q}{\beta+1}$$

$$\Rightarrow I_Q = \frac{I_{bias}}{1 + \frac{1}{\beta+1}} \approx 0.98 \times 0.5 = \underline{0.49 \text{ mA}}$$

The largest positive output is obtained when all of I_{bias} flows into the base of Q_N , resulting in

$$V_O = (\beta_N + 1) I_{bias} R_L \\ = 51 \times 0.5 \times 100 \Omega = \underline{2.55 \text{ V}}$$

The largest possible negative output voltage is limited by the saturation of Q_P to $-10 + V_{ESsat} = \underline{-10 \text{ V}}$.

To achieve a maximum positive output of 10 V without changing I_{bias} , β_N must be

$$10 = (\beta_N + 1) \times 0.5 \times 100 \Omega$$

$$\Rightarrow \beta_N = \underline{199}$$

Alternatively, if β_N is held at 50, I_{bias} must be increased so that

$$10 = 51 \times I_{bias} \times 100 \Omega$$

$$\Rightarrow I_{bias} = \underline{1.96 \text{ mA}}$$

for which,

$$I_Q = \frac{I_{bias}}{1 + \frac{1}{\beta+1}} = \underline{1.92 \text{ mA}}$$

1421 At 20°C , $I_Q = 1 \text{ mA} = I_S e^{(V_{BE}/V_T)}$

$$\Rightarrow I_S \text{ (at } 20^\circ\text{C)} = 3.78 \times 10^{-11} \text{ mA}$$

$$\text{At } 70^\circ\text{C}, I_S = 3.78 \times 10^{-11} \times (1.14)^{50}$$

$$= 2.64 \times 10^{-8} \text{ mA}$$

$$\text{At } 70^\circ\text{C}, V_T = 25 \frac{273+70}{273+20} = 29.3 \text{ mV}$$

$$\text{Then, } I_Q \text{ (at } 70^\circ\text{C)} = 2.64 \times 10^{-8} e^{0.6/0.0293} = \underline{20.7 \text{ mA}}$$

$$\text{Additional current} = 20.7 - 1 = 19.7 \text{ mA}$$

$$\text{Additional power} = 2 \times 20 \times 19.7 = \underline{788 \text{ mW}}$$

$$\text{Additional temperature rise} = 10 \times 0.788 = \underline{7.9^\circ\text{C}}$$

$$\text{At } 77.9^\circ: V_T = \frac{25}{2.93} (273+77.9) = 29.9 \text{ mV}$$

$$I_Q = 3.78 \times 10^{-11} \times (1.14)^{57.9} e^{0.6/0.0299} \\ = \underline{37.6 \text{ mA}}$$

c.c., etc.

1422 Refer to Fig. P 14.22.

$$0.100 = 1 (V_{GS3} - 1)^2$$

$$V_{GS3} = 1.316 \text{ V} = |V_{GS4}|$$

$$A_V = \frac{R_N}{R_L + R_{out}} = 0.49$$

$$\frac{1}{1 + R_{out}} = 0.19$$

$$\Rightarrow R_{out} = 0.01 \text{ k}\Omega = 10 \Omega$$

$$\text{But } R_{out} = (1/g_m) // (1/g_{s2})$$

$$= \frac{1}{2g_m} \Rightarrow g_m = 50 \text{ mA/V}$$

$$50 = k_1 (V_{GS1} - V_t)$$

$$= k_1 (1.316 - 1)$$

$$\Rightarrow k_1 = \frac{50}{1.316 - 1} = 158.2 \text{ mA/V}^2$$

$$M = \frac{158.2}{2} = \underline{79.1}$$

1423 From the peak positive output current 14

is 200 mA , the base current of Q_N can be as

high as $\frac{200}{\beta_N + 1} = \frac{200}{51} \approx 4 \text{ mA}$. We select $I_{bias} =$

5 mA , thus providing the multiplier with a minimum current of 1 mA .

Under quiescent conditions ($V_O = 0$ and $i_i = 0$)

the base current of Q_N can be neglected.

Selecting $I_R = 0.5 \text{ mA}$ leaves $I_{C1} = 4.5 \text{ mA}$.

To obtain a quiescent current of 2 mA in the output transistor, V_{BB} should be

$$V_{BB} = 2 V_T \ln \frac{2 \times 10^{-3}}{10^{-13}} = 1.19 \text{ V}$$

Then

$$R_1 + R_2 = \frac{V_{BB}}{I_R} = \frac{1.19}{0.5} = 2.38 \text{ k}\Omega$$

At a collector current of 4.5 mA , Q_1 has

$$V_{BE1} = V_T \ln \frac{4.5 \times 10^{-3}}{10^{-14}} = 0.671 \text{ V}$$

The value of R_1 can now be determined as

$$R_1 = \frac{0.671}{0.5} = \underline{1.34 \text{ k}\Omega}$$

and

$$R_2 = 2.38 - 1.34 = \underline{1.04 \text{ k}\Omega}$$

14.29 (a) $V_{BE} = 0.7 \text{ V}$ at 1 mA

14

At 0.5 mA , $V_{BE} = 0.7 + 0.025 \ln \frac{0.5}{1} = 0.683 \text{ V}$

Then $R_1 = \frac{0.683}{0.5} = 1.365 \text{ k}\Omega$

and $R_2 = 1.365 \text{ k}\Omega$

(b) For $I_{B1} = 2 \text{ mA}$, I_C increases to nearly 1.5 mA for which

$$V_{BE} = 0.7 + 0.025 \ln \frac{1.5}{1} = 0.710 \text{ V}$$

Note that $I_R = \frac{0.710}{1.365} = 0.52 \text{ mA}$ is very nearly equal to the assumed value of 0.50 mA , then no further iterations are required.

$$V_{BB} = 2 V_{BE} = 1.420 \text{ V}$$

(c) For $I_{B1} = 10 \text{ mA}$, assume that I_R remains constant at 0.5 mA , then $I_C = 1.5 \text{ mA}$

and $V_{BE} = 0.7 + 0.025 \ln \frac{1.5}{1} = 0.756 \text{ V}$

at which

$$I_R = \frac{0.756}{1.365} = 0.554 \text{ mA}$$

Then, $I_{C1} = 10 - 0.554 = 9.45 \text{ mA}$

and $V_{BE} = 0.7 + 0.025 \ln \frac{9.45}{1} = 0.756 \text{ V}$

Then $V_{BB} = 2 \times 0.756 = 1.512 \text{ V}$

(d) Now for $\beta = 100$,

14

$$I_{R1} = \frac{0.756}{1.365} = 0.554 \text{ mA}$$

$$I_{R2} = 0.554 + \frac{9.45}{101} = 0.648 \text{ mA}$$

$$I_C = 10 - 0.648 = 9.352 \text{ mA}$$

Then, $V_{BE} = 0.7 + 0.025 \ln \frac{9.352}{1} = 0.756 \text{ V}$

$$V_{BB} = 0.756 + I_{R2} R_2$$

$$= 0.756 + 0.648 \times 1.365$$

$$= 1.641 \text{ V}$$

14.25 Power rating = $\frac{130 - 30}{2} = 50 \text{ W}$

$$I_{Cav} \leq \frac{50}{20} = 2.5 \text{ A}$$

14.26 $\theta_{JA} = \frac{150 - 25}{0.2} = 625 \text{ }^\circ\text{C/W} = 0.625 \text{ }^\circ\text{C/mW}$

At 70°C , Power rating = $\frac{150 - 70}{0.625} = 128 \text{ mW}$

$$T_J = 50 + 0.625 \times 100 = 112.5 \text{ }^\circ\text{C}$$

14.27 $T_J \leq 50 + 3 \times 30 = 140 \text{ }^\circ\text{C}$

$$V_{BE} = 800 - 2 \times (140 - 25) = 570 \text{ mV}$$

$$= 0.57 \text{ V}$$

14.28 (a) $\theta_{JA} = \frac{T_{Jmax} - T_{A0}}{P_{D0}}$

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$$= \frac{100 - 25}{2} = 37.5 \text{ }^\circ\text{C/W}$$

(b) At $T_A = 50^\circ\text{C}$,

$$P_{Dmax} = \frac{T_{Jmax} - T_A}{\theta_{JA}}$$

$$= \frac{100 - 50}{37.5} = 1.33 \text{ W}$$

(c) $T_J = 25^\circ + 37.5 \times 1 = 62.5 \text{ }^\circ\text{C}$

14.29 $T_C - T_A = \theta_{CA} P_D$

$$= (\theta_{CS} + \theta_{SA}) P_D$$

$$\Rightarrow P_D = \frac{T_C - T_A}{\theta_{CS} + \theta_{SA}} = \frac{90 - 30}{0.2 + 0.1} = 100 \text{ W}$$

$$T_J - T_C = \theta_{JC} P_D$$

$$130 - 90 = \theta_{JC} \times 100$$

$$\Rightarrow \theta_{JC} = 0.4 \text{ }^\circ\text{C/W}$$

14.30 $\theta_{JC} = \frac{T_J - T_C}{P_D} = \frac{180^\circ - 30^\circ}{50} = 2.6 \text{ }^\circ\text{C/W}$

$$T_J - T_S = \theta_{JS} P_D$$

$$180^\circ - T_S = (\theta_{JC} + \theta_{CS}) P_D$$

$$\Rightarrow T_S = 180 - (2.6 + 0.4) \times 30 = 84^\circ$$

$$T_S - T_A = \theta_{SA} P_D$$

14

$$84 - 39 = \theta_{SA} \times 30$$

$$\Rightarrow \theta_{SA} = 1.5 \text{ }^\circ\text{C/W}$$

Required heat-sink length = $\frac{4.5 \text{ }^\circ\text{C/W/cm}}{1.5 \text{ }^\circ\text{C/W}} = 3 \text{ cm}$

14.31 $r_T = \frac{n V_T}{I_B} = \frac{2 \times 25 \times 10^{-3}}{0.5} = 0.1 \text{ }\Omega$

$$r_x \approx r_i - r_T = 0.98 - 0.1 = 0.85 \text{ }\Omega$$

14.32 $V_{B'E} = V_{BE} - I_B r_x$

$$= 1.05 - 0.19 \times 0.8$$

$$= 0.898 \text{ V (at } I_C = 5 \text{ A)}$$

For $I_C = 2 \text{ A}$,

$$V_{B'E} = 0.898 + n V_T \ln \frac{2}{5}$$

$$= 0.898 + 2 \times 0.025 \ln \left(\frac{2}{5}\right)$$

$$= 0.852 \text{ V}$$

$$V_{BE} = 0.852 + I_B r_x$$

$$= 0.852 + (0.19 \times \frac{2}{5}) \times 0.8$$

$$= 0.913 \text{ V}$$

14.33 (a) For $R_L = \infty$:

At $V_I = 0$ V,

$$I_{B1} = I_{B2} = \frac{2.87}{200}$$

$$I_I = I_{B2} - I_{B1} = 0$$

At $V_I = +10$ V,

$$I_{B1} = \frac{0.88}{200} \text{ mA} = 4.4 \text{ } \mu\text{A}$$

$$I_{B2} = \frac{4.87}{200} \text{ mA} = 24.4 \text{ } \mu\text{A}$$

$$I_I = I_{B2} - I_{B1} = 20 \text{ } \mu\text{A}$$

At $V_I = -10$ V,

$$I_{B1} = \frac{4.87}{200} \text{ mA} = 24.4 \text{ } \mu\text{A}$$

$$I_{B2} = \frac{0.88}{200} \text{ mA} = 4.4 \text{ } \mu\text{A}$$

$$I_I = I_{B2} - I_{B1} = -20 \text{ } \mu\text{A}$$

(b) For $R_L = 100 \text{ } \Omega$:

At $V_I = 0$, $I_I = 0$

At $V_I = +10$ V,

$$I_{B1} = \frac{0.38}{200} = 1.9 \text{ } \mu\text{A}$$

$$I_{B2} = \frac{4.87}{200} = 24.4 \text{ } \mu\text{A}$$

$$I_I = I_{B2} - I_{B1} = 22.5 \text{ } \mu\text{A}$$

At $V_I = -10$ V, $I_I = -22.5 \text{ } \mu\text{A}$



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Output Resistance at $V_I = 0$:

As a result of 2 paths to output,

$$R_{out} = \frac{1}{2} (R_3 + r_{e3} + \frac{r_{e1}}{\beta_1 + 1})$$

$$\text{where } r_{e1} \approx r_{e3} = \frac{25 \text{ mV}}{40 \text{ } \mu\text{A}} = 0.625 \text{ } \Omega$$

$$\text{Thus, } R_{out} = \frac{1}{2} (0.74 + 0.625 + \frac{0.625}{51}) = 0.69 \text{ } \Omega$$

Output Voltage for $V_I = +1$ V and $R_L = 2 \text{ } \Omega$

To solve the solution, let $V_O \approx 1$ V,

$$\text{then } I_L \approx \frac{1}{2} = 0.5 \text{ A} = 500 \text{ mA}$$

$$I_{B3} = \frac{200}{50} = 10 \text{ mA}$$

$$I_{E1} \approx \frac{10 - 1 - 0.7}{0.215} - 10 = 28.6 \text{ mA}$$

for which,

$$V_{EB1} = 0.7 + 0.025 \ln \frac{28.6}{10} = 0.726 \text{ V}$$

$$V_{B3} = 1 + 0.726 = 1.726 \text{ V}$$

Assuming $I_{E4} \approx 0$,

$$V_{BE3} \approx 700 + 25 \ln \frac{300}{3 \times 10} = 770 \text{ mV}$$

$$\text{Thus, } I_L = \frac{1.726 - 0.770}{0.74 + 2} = 0.349 \text{ A}$$

for which

$$V_O = 2 \times 0.349 = 0.698 \text{ V}$$

Then, the voltage drop across the series combination of R_4 and the EB junction of Q_4 can be found as follows,

$$V_{B4} = V_{E4} \approx 1 - 0.74 = 0.26 \text{ V}$$

leaving a drop across the series combination of R_4 and EBJ4 of $0.698 - 0.26 = 0.438$ V. It follows that $I_{E4} \approx 0$, as assumed.

Iterative solution:

$$I_L \approx 0.35 \text{ A}$$

$$I_{B3} \approx \frac{0.35}{51} \approx 7 \text{ mA}$$

$$I_{E1} \approx \frac{10 - 1 - 0.73}{0.215} - 7 = 31.5 \text{ mA}$$

$$V_{EB3} = 0.7 + 0.025 \ln \frac{31.5}{10} = 0.729 \text{ V}$$

$$V_{B3} = 1 + 0.729 = 1.729 \text{ V}$$

$$V_{BE3} = 0.7 + 25 \ln \frac{350}{3 \times 10} = 0.761 \text{ V}$$

$$I_L = \frac{1.729 - 0.761}{0.74 + 2} = 0.353 \text{ A}$$

$$V_O = 2 \times 0.353$$

$$= 0.706 \text{ V}$$

14

14.34 For the design process:

At $V_I = +5$ V, the voltage across

R_1 , V_{R1} , is

$$V_{R1} = 10 - 5 - 0.7 = 4.3 \text{ V}$$

and, $I_{R1} = 2 \times 10^{-4}$ A (to allow for I_{B3} of as much as 10 mA and only a 2 to 1 variation in I_{E1})

$$\text{Thus, } R_1 = \frac{4.3}{20} = 215 \text{ } \Omega$$

Correspondingly,

$$R_2 = 215 \text{ } \Omega$$

Now, for $V_I = 0$ and $V_{EB1} \approx 0.7$ V

$$I_{R1} = \frac{10 - 0.7 - 0}{215} = 43.3 \text{ mA}$$

for which $V_{EB1} = 700 + 25 \ln \frac{43.3}{10} = 736.6 \text{ mV}$

Since $I_Q = 40 \text{ mA}$ and $I_{B3} = 3 I_{E1}$,

$$V_{BE3} = 700 + 25 \ln \frac{40}{3 \times 10} = 707.2 \text{ mV}$$

$$\text{Thus, } R_3 = \frac{736.6 - 707.2}{40 \text{ mA}} = 0.74 \text{ } \Omega$$

Correspondingly,

$$R_4 = 0.74 \text{ } \Omega$$

14.35 $I_{E1} = I_{E2} \approx 2 \text{ mA}$

$I_Q = I_{E3} + I_{E4} = I_{E1} + I_{E2}$

Thus, $I_Q \approx 2 \text{ mA}$

More precisely, $I_Q = 1.96 \text{ mA}$

$I_{B1} = I_{B2} = \frac{2}{\beta_1} \approx 0.04 \text{ mA}$

The net input bias

current is ideally zero

For a β mismatch of 10%

$I_X = 0.10 \times 0.04 \text{ mA}$

$\approx 4 \mu\text{A}$

For $R_L = 100 \Omega$, the equivalent half-circuit becomes:

Thus, $2R_i = (\beta_1 + 1)[r_{e1} + (2R_L)]$

where $r_{e1} = r_{e2} = \frac{25}{I_E}$

$\approx 12.5 \Omega$

$R_i = \frac{25}{I_E} [0.0125 + 51(0.0125 + 0.200)]$

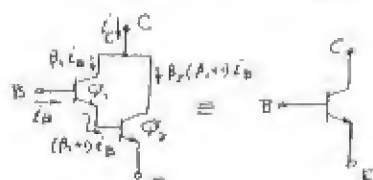
$\approx 275.7 \Omega$

The gain can be determined using the equivalent half-circuit, as follows:

$A_v = \frac{v_o}{v_i} = \frac{2R_L}{2R_L + r_{e1} + \frac{r_{e1}}{\beta_1 + 1}}$

$= \frac{2 \times 100}{2 \times 100 + 12.5 + \frac{12.5}{51}} = 0.94 \text{ V/V}$

14.36



$I_C = \beta_1 I_{B1} + \beta_2 (\beta_1 + 1) I_{B2}$

$\beta_{eq} = \frac{I_C}{I_{B1}} = \beta_1 + \beta_2 (\beta_1 + 1)$

$\approx \beta_1 \beta_2$ (for $\beta_1 \gg 1$ and $\beta_2 \gg 1$)

If the composite transistor is operated as a collector current I_C , then

$I_B = \frac{I_C}{\beta_1 + \beta_2 (\beta_1 + 1)}$

$I_{C1} = \frac{\beta_1}{\beta_1 + \beta_2 (\beta_1 + 1)} I_C \approx I_C / \beta_2$

$I_{C2} = \frac{\beta_2 (\beta_1 + 1) I_C}{\beta_1 + \beta_2 (\beta_1 + 1)} \approx I_C$

Then,

$V_{BE2} = V_{BE} (1 \text{ mA}) + V_T \ln \left(\frac{I_C}{1 \text{ mA}} \right)$

$V_{BE1} = V_{BE} (1 \text{ mA}) + V_T \ln \left(\frac{I_C}{\beta_1 \times 1 \text{ mA}} \right)$

$V_{BEeq} = V_{BE1} + V_{BE2}$
 $= 2V_{BE} (1 \text{ mA}) + V_T \ln \left(\frac{I_C^2}{\beta_1} \right)$

$\tau_{e2} = \frac{V_T}{I_{E2}} \approx \frac{V_T}{I_{C2}} \approx \frac{V_T}{I_C}$

$\tau_{e1} = \frac{V_T}{I_{E1}} \approx \frac{V_T}{I_{C1}} \approx \frac{V_T}{I_C / \beta_1} = \beta_1 \tau_{e2}$

$\tau_{Teq} = (\beta_1 + 1) [\tau_{e1} + (\beta_2 + 1) \tau_{e2}]$

$\approx \beta_1 [\beta_2 \tau_{e1} + \beta_2 \tau_{e2}]$

$= 2\beta_1 \beta_2 \tau_{e2} \approx 2\beta_1 \beta_2 \left(\frac{V_T}{I_C} \right)$

To determine $g_{m,eq}$, apply a signal v_{be} and find the corresponding current i_c ,

$i_c = i_{c1} + i_{c2} = g_{m1} v_{be1} + g_{m2} v_{be2}$
 $= g_{m1} v_{be} \frac{\tau_{e1}}{\tau_{e1} + (\beta_1 + 1) \tau_{e2}} + g_{m2} \frac{(\beta_2 + 1) \tau_{e2}}{\tau_{e2} + (\beta_2 + 1) \tau_{e1}}$

$i_c \approx v_{be} \frac{1}{2\beta_2 \tau_{e2}} + \frac{\beta_1}{2\beta_1 \tau_{e1}} v_{be}$

$g_{m,eq} = \frac{i_c}{v_{be}} \approx \frac{1}{2\tau_{e1}} = \frac{1}{2} \frac{I_C}{V_T}$

For operation at $I_C = 10 \text{ mA}$:

$\beta_{eq} = \beta_1 \beta_2 = 50^2 = 2500$

$V_{BEeq} = 1.4 + 0.025 \ln \frac{10^3}{50}$
 $\approx 1.42 \text{ V}$

$\tau_{Teq} \approx 2 \times 50 \times 50 \times \frac{25}{10} = 12.5 \text{ k}\Omega$

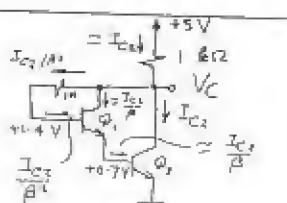
$g_{m,eq} \approx \frac{1}{2} \times \frac{10}{25} = 200 \text{ mA/V}$

14.37 DC analysis:

$5 = I_{C2} \times 1 \text{ k}\Omega$
 $+ \frac{I_{C2}}{\beta_2} \times 1 \text{ M}\Omega$
 $+ 1.4$

$I_{C2} = \frac{3.6}{1 + \frac{1000}{100 \times 100}}$
 $\approx 3.3 \text{ mA}$

$I_{C1} = \frac{3.3}{100} = 0.033 \text{ mA}$
 $V_C \approx 1.7 \text{ V}$



14.37 CONT'D

$$i_c = g_m v_{ce1}$$

$$= g_m \frac{(\beta_2 + 1) r_{e2}}{r_{e1} + (\beta_2 + 1) r_{e2}} v_i$$

But $r_{e1} = \frac{V_T}{I_{E1}} = \frac{V_T}{I_{E2} \beta_2}$ $r_{e2} (\beta_2 + 1)$

$$\text{Then, } i_c \approx \frac{v_i}{2 r_{e2}}$$

$$g_{mxy} \approx \frac{i_c}{v_i} = \frac{1}{2 r_{e2}}$$

$$= \frac{1}{2 \times (25/0.5)} = 66 \text{ mA/V}$$

$$v_o \approx -i_c \times 1 \text{ k}\Omega$$

$$= -g_{mxy} v_i \times 1 \text{ k}\Omega$$

$$\frac{v_o}{v_i} = -66 \times 1 = -66 \text{ V/V}$$

To find R_{in} ,

$$i_i = i_{b1} + i_{b2} \text{ (looking in)}$$

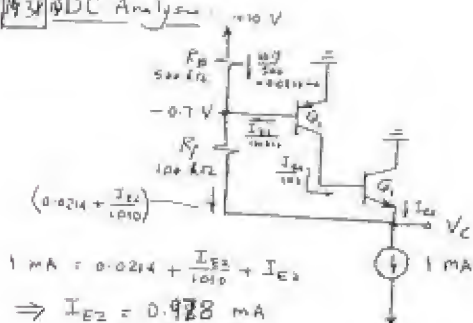
$$\approx \frac{i_c}{\beta_2} + \frac{v_i - v_o}{1 \text{ M}\Omega}$$

$$= \frac{v_i}{2 \beta_2 r_{e2}} + \frac{67 v_i}{1 \text{ M}\Omega}$$

$$= v_i \left[\frac{1}{2 \times 100 \times 25 \times 10^{-3}} + \frac{67}{1 \text{ M}\Omega} \right] = 75.6 v_i \text{ (A)}$$

$$R_{in} = \frac{v_i}{i_i} = \frac{1}{75.6} \text{ M}\Omega = 13.6 \text{ k}\Omega$$

14.38 DC Analysis



$$1 \text{ mA} = 0.0214 + \frac{I_{E2}}{101} + I_{E2}$$

$$\Rightarrow I_{E2} = 0.978 \text{ mA}$$

$$I_{C2} = 0.99 \times 0.978 = 0.97 \text{ mA}$$

$$I_{C1} = \frac{0.978}{101} = 9.7 \text{ }\mu\text{A}$$

$$V_C = -0.7 - 100 \left(0.0214 + \frac{0.978}{101} \right)$$

$$= -2.94 \text{ V}$$

(b) Small-signal parameters:

$$g_{m1} = \frac{9.7 \times 10^{-6}}{25 \times 10^{-3}} = 0.388 \text{ mA/V}$$

$$r_{\pi 1} = \frac{\beta_1}{g_{m1}} = 25.77 \text{ k}\Omega$$

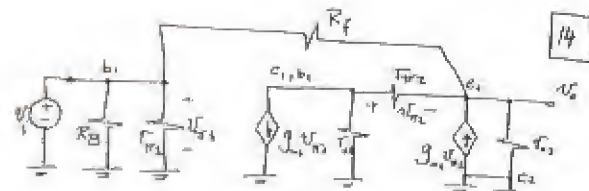
$$r_{o1} = \frac{|V_A|}{I_{C1}} = \frac{100}{9.7 \text{ }\mu\text{A}} = 10.31 \text{ M}\Omega$$

$$g_{m2} = \frac{0.97 \times 10^{-3}}{25 \times 10^{-3}} = 38.8 \text{ mA/V}$$

$$r_{\pi 2} = \frac{\beta_2}{g_{m2}} = 2.58 \text{ k}\Omega$$

$$r_{o2} = |V_A|/I_{C2} = 103.1 \text{ k}\Omega$$

14



Node equation at b_2 :

$$g_{m1} v_{\pi 1} + \frac{v_{b2}}{r_{\pi 1}} + \frac{v_{\pi 2}}{r_{\pi 2}} = 0$$

But $v_{b2} = v_o + v_{\pi 2}$, then

$$g_{m1} v_{\pi 1} + \frac{v_o + v_{\pi 2}}{r_{\pi 1}} + \frac{v_{\pi 2}}{r_{\pi 2}} = 0$$

$$\Rightarrow v_{\pi 2} \left(\frac{1}{r_{\pi 1}} + \frac{1}{r_{\pi 2}} \right) = - \left(\frac{v_o}{r_{\pi 1}} + g_{m1} v_{\pi 1} \right)$$

$$\text{or, } v_{\pi 2} = - \frac{\frac{v_o}{r_{\pi 1}} + g_{m1} v_{\pi 1}}{\frac{1}{r_{\pi 1}} + \frac{1}{r_{\pi 2}}}$$

Node equation at output:

$$\frac{v_o}{r_{o1}} + \frac{v_o - v_{\pi 2}}{R_f} = g_{m2} v_{\pi 2} + \frac{1}{r_{o2}} v_{\pi 2}$$

$$= \left(g_{m2} + \frac{1}{r_{o2}} \right) v_{\pi 2}$$

$$= - \frac{\left(g_{m2} + \frac{1}{r_{o2}} \right) \left[\frac{v_o}{r_{\pi 1}} + g_{m1} v_{\pi 1} \right]}{\frac{1}{r_{\pi 1}} + \frac{1}{r_{\pi 2}}}$$

Substituting $v_{\pi 1} = v_i$ and collecting terms, results in

$$v_o \left[\frac{1}{r_{o1}} + \frac{1}{R_f} + \frac{\left(g_{m2} + \frac{1}{r_{o2}} \right)}{r_{\pi 1} \left(\frac{1}{r_{\pi 1}} + \frac{1}{r_{\pi 2}} \right)} \right]$$

$$= -v_i \left[\frac{g_{m1} \left(g_{m2} + \frac{1}{r_{o2}} \right)}{\frac{1}{r_{\pi 2}} + \frac{1}{r_{o2}}} - \frac{1}{R_f} \right]$$

$$\frac{v_o}{v_i} = - \frac{\frac{g_{m1} \left(g_{m2} + \frac{1}{r_{o2}} \right)}{\frac{1}{r_{\pi 2}} + \frac{1}{r_{o2}}} - \frac{1}{R_f}}{\frac{1}{r_{o1}} + \frac{1}{R_f} + \frac{g_{m2} + \frac{1}{r_{o2}}}{r_{\pi 1} \left(\frac{1}{r_{\pi 1}} + \frac{1}{r_{\pi 2}} \right)}}$$

Since $r_{\pi 2} \ll r_{o2}$,

$$\frac{v_o}{v_i} \approx - \frac{g_{m1} \left(g_{m2} r_{o2} + 1 \right) - \frac{1}{R_f}}{\frac{1}{r_{o1}} + \frac{1}{R_f} + \frac{1}{r_{\pi 1}} \left(g_{m2} r_{o2} + 1 \right)}$$

$$= - \frac{g_{m1} (\beta_2 + 1) - \frac{1}{R_f}}{\frac{1}{r_{o1}} + \frac{1}{R_f} + \frac{1}{r_{\pi 1}} (\beta_2 + 1)}$$

Since $\frac{1}{R_f} \ll g_{m1} (\beta_2 + 1)$

$$\frac{v_o}{v_i} \approx - \frac{g_{m1} (\beta_2 + 1)}{\left(\frac{1}{r_{o1}} + \frac{1}{R_f} \right) + \frac{1}{r_{\pi 1}} (\beta_2 + 1)}$$

Substituting $\beta_2 = \beta_N$ and noting that $\beta_N \gg 1$,

$$\frac{v_o}{v_i} \approx - g_{m1} \frac{1}{\beta_N \left(\frac{1}{r_{o2}} + \frac{1}{R_f} \right) + \frac{1}{r_{\pi 1}}}$$

$$= - g_{m1} \left[r_{o1} \parallel \beta_N (r_{o2} \parallel R_f) \right]$$

Q.E.D.

14.38 CONT'D

$$(c) \frac{V_E}{V_E} = -0.388 \left[10.31 \times 10^3 // 100 (103.1 // 100) \right] \quad [14]$$

$$= -1320 \text{ V/V}$$

$$R_{in} = R_B // R_{in} // \left[\frac{V_E - V_E}{R_E} \right]$$

$$= 500 // 25.77 // \left[\frac{R_E}{1 - \frac{V_E}{V_E}} \right]$$

$$= 500 // 25.77 // \frac{100}{1 + 1320}$$

$$= 500 // 25.77 // 0.0757$$

$$= 75.5 \Omega$$

[14.39] Refer to Fig. 14.27 (p. 1258).

The quiescent current through Q_1 and Q_2 is to be 2 mA. Then

$$V_{BE2} = V_{BE4} = 0.7 + 0.025 \ln \left(\frac{2}{10} \right) = 0.660 \text{ V}$$

For Q_1 and Q_2 , $I_C \approx \frac{I_E}{2} = 0.02 \text{ mA}$, then

$$V_{BE1} = V_{BE3} = 0.7 + 0.025 \ln \frac{0.02}{1} = 0.602 \text{ V}$$

$$I_{B1} = \frac{20 \mu\text{A}}{100} = 0.2 \mu\text{A}$$

$$I_{bias} = 100 \times 0.2 = 20 \mu\text{A}$$

$$I_{R1, R2} = \frac{1}{10} \times 20 \mu\text{A} = 2 \mu\text{A}$$

$$I_{C3} = 20 - 2 = 18 \mu\text{A}$$

$$V_{BE5} = 0.7 + 0.025 \ln \frac{0.018}{1} = 0.600 \text{ V}$$

$$V_{BB} = V_{BE1} + V_{BE2} + V_{BE5} = 1.864 \text{ V}$$

$$R_1 + R_2 = \frac{1.864}{2 \mu\text{A}} = 932 \text{ k}\Omega$$

$$R_1 = \frac{0.600}{2 \mu\text{A}} = 300 \text{ k}\Omega$$

$$R_2 = 932 - 300 = 632 \text{ k}\Omega$$

For $V_D = -10 \text{ V}$ and $R_L = 1 \text{ k}\Omega$:

$$I_L = \frac{-10}{1} = -10 \text{ mA}$$

Assume that the current through Q_2 becomes almost zero, then

$$I_{C4} = 10 \text{ mA}$$

i.e. the current through Q_4 increases by a factor of 5. It follows that the current through Q_3 must increase by the same factor, then V_{EB3} becomes:

$$V_{EB3} = 0.602 + 0.025 \ln 5$$

$$= 0.642 \text{ V (an increase of } 0.04 \text{ V)}$$

Let us check the current through Q_3 . Since we assumed Q_1 and Q_2 to be almost cut off, all of I_{bias} now flows through the V_{BE} string, an increase of $0.2 \mu\text{A}$. Assuming that most of the increase occurs in I_{C3} , V_{BE5} becomes:

$$V_{BE5} = 0.7 + 0.025 \ln \frac{0.022}{1} = 0.600 \text{ V}$$

Then the voltage across the V_{BE} - multiplier remains approximately constant and the voltage ($V_{BE1} + V_{BE2}$) decreases by the same value that V_{EB3} increases. That is:

$$V_{BE1} + V_{BE2} = 0.660 + 0.602 - 0.04$$

Since the current through each of Q_1 and Q_2 decreases by the same factor (call it m),

$$0.025 \ln m + 0.025 \ln m = -0.04 \text{ V}$$

$$\Rightarrow m = 0.45$$

$$\text{Then } I_{C2} = 0.45 \times 2 = 0.9 \text{ mA}$$

New iteration: $I_{C4} = 10.9 \text{ mA}$ (an increase by a factor of 5.5)

$$V_{EB1} = 0.602 + 0.025 \ln 5.5$$

$$= 0.645 \text{ V}$$

$$V_L \approx -10.645 \text{ V}$$

For $V_D = +10 \text{ V}$ and $R_L = 1 \text{ k}\Omega$:

Assume that Q_4 is now conducting a negligible current. Then, $I_{C2} \approx I_L = 10 \text{ mA}$. i.e. the current through each of Q_1 and Q_2

increases by a factor of 5. Then

$$V_{BE2} = 0.66 + 0.025 \ln 5$$

$$= 0.700 \text{ V}$$

$$V_{BE1} = 0.602 + 0.025 \ln 5.5 = 0.642 \text{ V}$$

$$I_{B1} = 5 \times 0.2 = 1 \mu\text{A}$$

The decrease through the multiplier becomes $19 \mu\text{A}$, and assuming that most of the decrease occurs in I_{C5} ,

$$V_{BE5} = 0.7 + 0.025 \ln \frac{0.017}{1}$$

$$= 0.598 \text{ V}$$

Then the voltage across the multiplier becomes

$$V_{BB} = 0.598 \times \frac{932}{300} = 1.858 \text{ V}$$

It follows that V_{EB3} becomes

$$V_{EB3} = 1.858 - 0.700 - 0.642 = 0.516 \text{ V}$$

i.e. V_{EB3} decreases by $0.600 - 0.516 = 0.084 \text{ V}$

and corresponding I_{C3} decreases by a factor of $e^{\frac{-0.084}{0.025}} = 0.035$. Hence the I_{C4} becomes $0.035 \times 2 = 0.07 \text{ mA}$, close to the zero value assumed. Then no further iteration are required and

$$V_D \approx 10 + 0.7 + 0.642 - 1.858$$

$$= 9.484 \text{ V}$$

14.40 Refer to Exercise 14.13 and Fig. 14.28.

Now Q_5 has $I_S = 10^{-13}$ A. Then,

$$2 \times 10^{-3} = 10^{-13} e^{V_{BE}/V_T}$$

$$V_{BE} = 0.025 \ln \frac{2 \times 10^{-3}}{10^{-13}}$$

$$= 0.593 \text{ V}$$

$$R_{E1} = \frac{0.593}{150 \mu\text{A}} \approx 4 \Omega$$

For a maximum peak current of $100 \mu\text{A}$, the voltage drop across R_{E1} is 400 mV and its collector current is $10^{-13} e^{400/25} = 0.89 \mu\text{A}$

14.41 Refer to Exercise 14.13 and Fig. 14.28.

$$2 \times 10^{-3} = 10^{-14} e^{V_{BE}/V_T}$$

$$\Rightarrow V_{BE} = 0.650 \text{ V}$$

$$R_{E1} = \frac{0.650 \text{ V}}{50 \mu\text{A}} = 13 \Omega$$

For a peak output current of $33.3 \mu\text{A}$,

$$V_{BE} = 13 \times 33.3 = 433 \text{ mV}$$

$$I_{CS} = 10^{-14} e^{433/25} = 0.33 \mu\text{A}$$

14.42 Refer to the circuit of Fig. 14.30 (P.1402).

Resistors R_2 and R_3 control the gain,

$$A_v = -\frac{2R_1}{R_2} \quad (\text{See analysis on pages 681-682})$$

Resistor R_3 controls the gain alone. Resistor R_2 affects both the gain and the dc output level. To see the latter point, equate I_2 and I_3 from equations (1.43) and (1.44) to obtain

$$\frac{V_S - 3V_{BE}}{R_1} = \frac{V_O - 2V_{BE}}{R_3}$$

$$\Rightarrow V_O = 2V_{BE} + \frac{R_3}{R_1} V_S - \frac{2R_3}{R_1} V_{BE}$$

$$= \frac{R_3}{R_1} V_S + (2 - \frac{2R_3}{R_1}) V_{BE}$$

$$\text{For } V_O = \frac{1}{2} V_S, \text{ we need } \frac{R_3}{R_1} = \frac{1}{2}$$

$$R_2 = \frac{R_1}{2} = \frac{20}{2} = 10 \text{ k}\Omega$$

To keep the gain unchanged, we must change R_3 so that

$$\frac{2R_3}{R_1} = 50$$

$$R_3 = \frac{2 \times (50/1)}{20} = \frac{5}{2} = 2.5 \text{ k}\Omega$$

14.43 Refer to Fig. P.14.42.

$$2 \times 10^{-3} = 10^{-14} e^{V_{EB5}/V_T}$$

$$V_{EB5} = 0.025 \ln (2 \times 10^{-3})$$

$$= 0.650 \text{ V}$$

$$R = \frac{0.650 \text{ V}}{150 \mu\text{A}} = 4.3 \Omega$$

For a peak output current of $100 \mu\text{A}$,

$$V_{EB5} = 430 \text{ mV}$$

$$I_{CS} = 10^{-14} e^{430/25} = 0.3 \mu\text{A}$$

14.44 Refer to Fig. 14.29 (P.1260)

$$\text{At } 125^\circ\text{C}, V_Z = 6.8 + (125 - 25) \times 2 = 7.0 \text{ V}$$

$$V_{E1} = 7.0 - (0.7 - 100 \times 10^{-3})$$

$$= 6.5 \text{ V}$$

$$V_{BE2} = 0.5 \text{ V}$$

$$R_2 = \frac{0.5 \text{ V}}{100 \mu\text{A}} = 5 \text{ k}\Omega$$

$$R_1 = \frac{6.5 - 0.5}{100 \mu\text{A}} = 60 \text{ k}\Omega$$

$$\text{At } 25^\circ\text{C}, V_Z = 6.8 \text{ V}, V_{E1} = 6.8 - 0.7 = 6.1 \text{ V}$$

$$V_{B2} = 6.1 \times \frac{2}{60+5} = 0.469 \text{ V}$$

$$I_{C2} = 100 e^{(469-700)/25} = 0.01 \mu\text{A}$$

14.45 Refer to the circuit in Fig. 14.30

$$V_{B1} \approx 0$$

$$V_{E1} \approx +0.7 \text{ V}$$

$$V_{E3} \approx +1.4 \text{ V}$$

$$V_{C10} = 20 - 0.7 = 19.3 \text{ V}$$

$$I_{E3} = \frac{19.3 - 1.4}{50} = 0.358 \text{ mA}$$

$$I_{B3} = I_{E1} = \frac{0.358}{21} = 17.05 \mu\text{A}$$

$$I_{B1} = \frac{17.05}{21} = 0.81 \mu\text{A}$$

$$V_{B1} = 0.81 \mu\text{A} \times 150 \text{ k}\Omega = 0.122 \text{ V} \approx 0 \checkmark$$

$$i.e. I_{E1} = I_{E2} \approx 17 \mu\text{A}$$

$$I_{E3} = I_{E4} = 358 \mu\text{A}$$

$$I_{E5} = I_{E6} = \frac{30}{21} \times 358 = 501 \mu\text{A}$$

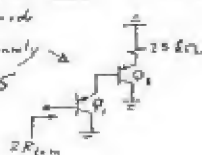
$$I_{R2} = I_{R1} = 358 \mu\text{A}$$

$$V_O = 0.12 + 1.4 + 25 \text{ k}\Omega \times 0.358 \text{ mA}$$

$$= 10.5 \text{ V}$$

14.46 The equivalent common-mode half circuit is approximately →
From the results of Problem 14.45

Above: $I_{E1} = 17 \mu A$
 $I_{E3} = 0.158 \text{ mA}$



$$r_{e1} = \frac{1V_A}{I_{E1}}$$

Assume $1V_A$ for all transistors = 100 V.

$$r_{e1} \approx \frac{100}{17 \mu A} = 5.9 \text{ M}\Omega$$

$$r_{e3} = \frac{100}{0.158} = 271.3 \text{ k}\Omega$$

Assume $r_{\pi} = 10 \beta r_e$

$$r_{\pi 1} = 10 \times 20 \times 5.9 = 1180 \text{ M}\Omega$$

$$r_{\pi 3} = 10 \times 20 \times 271.3 = 55.9 \text{ M}\Omega$$

Now, $2R_{in} = r_{\pi 1} \parallel \left[(\beta+1) \left(r_{e3} \parallel \left[r_{\pi 3} \parallel (\beta+1)(25 \parallel r_{e1}) \right] \right) \right]$
 $= 1180 \text{ M}\Omega \parallel \left[21 \left[5.9 \parallel 55.9 \parallel 21(25 \parallel 271.3 \parallel 20) \right] \right] \text{ M}\Omega$
 $\approx 21 \times 21 \times (25 \parallel 271.3) \text{ k}\Omega$
 $= 10.1 \text{ M}\Omega$

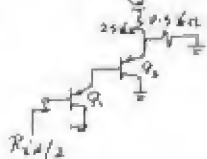
If we neglect all r_e 's and r_{π} 's

$$2R_{in} \approx (\beta+1)^2 \times 25 \text{ k}\Omega$$

$$= 11 \text{ M}\Omega \text{ (close enough!)} \quad 25 \text{ k}\Omega$$

$$R_{in} = 5.5 \text{ M}\Omega$$

To find R_{id} we use the equivalent differential half-circuit →



$$R_{id}/2 = (\beta+1) [r_{e1} + (\beta+1)(r_{e3} + 0.5 \parallel 25)]$$

$$r_{e1} = \frac{25 \text{ mV}}{17 \mu A} = 1.47 \text{ k}\Omega$$

$$r_{e3} = \frac{25 \text{ mV}}{0.158 \text{ mA}} = 61.8 \Omega$$

$$R_{id} = 2 \times 21 [1.47 + 21(0.0618 + 0.49)]$$

 $= 556 \text{ k}\Omega$

To find $G_m = \frac{2i_L}{v_{id}}$

$$i_{c3} = \alpha_3 i_{e3}$$

$$= \alpha_3 \frac{v_{id}/2}{(0.5 \parallel 25) + r_{e3} + \frac{r_{\pi 3}}{\beta+1}}$$

$$= \frac{20}{21} \times \frac{v_{id}}{(0.5 \parallel 25) + 0.0618 + \frac{1.47}{21}}$$

$$= 0.757 \text{ V}_{id}$$

$$i_L = \frac{i_{c3}}{1 + \frac{2}{\beta_{npn}}} = 0.98 i_{c3} = 0.98 \times 0.757 \text{ V}_{id}$$

$$G_m = \frac{2i_L}{v_{id}} = 2 \times 0.98 \times 0.757 = 1.5 \text{ mA/V}$$

14.47 Using Fig. 14.32 (p.1264) for 8Ω load, we can see that $V_S = 15 \text{ V}$ allows more than 1.5 W power dissipation for some pure signals. Thus we use

$$V_S = 14 \text{ V}$$

For THD = 3%, $P_{max} = 1.9 \text{ W}$

$$1.9 = V_o^2 / R_L = V_o^2 / 8$$

$$V_o = \sqrt{8 \times 1.9}$$

$$P_{dc-to-Rd} \text{ output sinusoid} = 2\sqrt{2} \sqrt{8 \times 1.9} = 11 \text{ V}$$

$$14.48 f_c \approx \frac{G_m}{2\pi C}$$

$$= \frac{1.6 \times 10^{-3}}{2\pi \times 10 \times 10^{-9}} = 25.5 \text{ MHz}$$

With feedback that results in a closed-loop gain of 50,

$$f_L = \frac{25.5}{50} = 509 \text{ kHz}$$

14.49 Refer to Fig. 14.33

For $I_L = 1 \text{ A}$, $i_{c5} \approx 1 \text{ A}$ and $i_{B5} = \frac{1 \text{ A}}{50} = 20 \text{ mA}$

For $I_L = 20 \text{ mA}$, $i_{B5} = 0.1 \times 20 = 18 \text{ mA}$,

$$i_{c5} = 2 \text{ mA} \quad i_{B5} = \frac{2}{50} = 0.04 \text{ mA}$$

$$i_{c3} = \frac{50}{21} \times 18 = 17.65 \text{ mA}$$

$$i_{B3} = i_{c3} - i_{B5} = 17.61 \text{ mA}$$

$$\text{Thus, } R_3 = \frac{0.7}{17.61} \times 31.8 \approx 40 \Omega$$

$$\text{Similarly, } R_2 = 40 \Omega$$

Since $i_{B5} \leq 20 \text{ mA}$, $i_{c3} \leq \frac{0.7 \text{ V}}{40 \Omega} + 20 \text{ mA}$
i.e. $i_{c3} \leq 37.5 \text{ mA}$

$$i_{B3} \leq \frac{37.5}{50} = 0.75 \text{ mA}$$

Allowing for a factor of safety of 2, we select R_1 so that the current through it

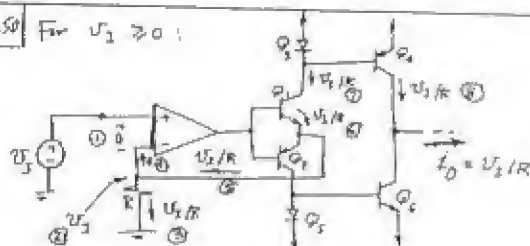
is 1.5 mA. Now, for $V_S = 11 \text{ V}$, $V_{E1} = 10.7 \text{ V}$,

$$R_1 = \frac{15 - 10.7}{1.5} = 2.2 \text{ k}\Omega$$

Similarly,

$$R_2 = 2.2 \text{ k}\Omega$$

4.50 For $V_2 \geq 0$:



For $V_2 \leq 0$, Q_1 , Q_3 and Q_4 make the roles of Q_1 , Q_2 and Q_3 , respectively.

For $\beta = 100$, $i_{C1} = 0.99 V_2 / R$ and

$$i_{C1} = i_{C1} \frac{1}{1 + \frac{1}{\beta}} = 0.99 \frac{V_2}{R} \frac{1}{1 + \frac{1}{100}} = 0.99 \frac{V_2}{R}$$

That is, the current is lower than the ideal value by approximately 3%.

4.51 Refer to Eq. 14.34

$$\frac{V_D}{V_2} = 2K = 2 \left(1 + \frac{R_2}{R_1} \right) = 10$$

$$\Rightarrow \frac{R_2}{R_1} = 4$$

$$R_2 = 40 \text{ k}\Omega$$

$$\text{Also, } K = \frac{R_2}{R_1} = 5$$

$$\Rightarrow R_1 = 50 \text{ k}\Omega$$

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$$\text{For } \frac{V_D}{V_2} = 10 = 1 + \frac{R_2 + R_3}{R_1}$$

and selecting $R_1 = 1 \text{ k}\Omega$

$$R_2 + R_3 = 9 \text{ k}\Omega$$

Now to keep the outputs complementary

$$\frac{R_2}{R_1} = 1 + \frac{R_3}{R_1}$$

$$\Rightarrow R_1 = 1 + R_3$$

$$\text{Thus } R_2 = 1 \text{ k}\Omega \text{ and } R_3 = 5 \text{ k}\Omega$$

4.53 Normally, (Eq. 14.46)

$$i_D = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_t)^2$$

For velocity saturation, (Eq. 14.47)

$$i_D = \frac{1}{2} C_{ox} W v_{sat} (V_{GS} - V_t)$$

Equating the two expressions (at the boundary)

$$\mu_n \frac{1}{2} (V_{GS} - V_t) = v_{sat}$$

$$\Rightarrow L = \frac{\mu_n (V_{GS} - V_t)}{v_{sat}}$$

For $\mu_n = 500 \text{ cm}^2/\text{V}\cdot\text{s}$, $V_{GS} = 5 \text{ V}$, $V_t = 2 \text{ V}$,

$$v_{sat} = 3 \times 10^6 \text{ cm/s}$$

$$L = \frac{500 (5 - 2)}{3 \times 10^6} = 3 \times 10^{-4} \text{ cm} = 3 \text{ }\mu\text{m}$$

Velocity saturation begins at

$$i_D = \frac{1}{2} C_{ox} W v_{sat} (V_{GS} - V_t)$$

$$= \frac{1}{2} \times 400 \times 10^{-6} \times 10^{-3} \times 10^{-6} \times 3 \times 10^6 \times 10^{-2} (5 - 2)$$

$$= 3 \text{ }\mu\text{A}$$

At high currents,

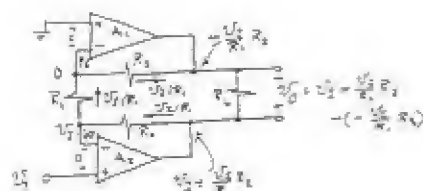
$$g_m = \frac{\partial i_D}{\partial V_{GS}} = \frac{1}{2} C_{ox} W v_{sat}$$

$$= \frac{1}{2} \times 400 \times 10^{-6} \times 10^{-3} \times 10^{-6} \times 3 \times 10^6 \times 10^{-2}$$

$$= 1 \text{ A/V}$$

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4.52



$$\frac{V_D}{V_2} = 1 + \frac{R_2}{R_1} + \frac{R_2}{R_1}$$

The largest source-sink output is obtained when the voltage at the output of one op amp (say A_1) is $+13 \text{ V}$ and that at the output of the other op amp (A_2) is -13 V , resulting in a 26-V peak output (52 V peak-to-peak).

8.54 Refer to the circuit in Fig. 14.38

For $I_{Q_N} = I_{Q_P} = 10 \text{ mA}$ $\Rightarrow C_{ox} \mu (V_{GS} - V_t)^2$
 $10 = 100 (V_{GS} - 2)^2$

$\Rightarrow V_{GS} = 2.32 \text{ V}$

$V_G = 2|V_{GS}| = 4.63 \text{ V}$

For $I_D = 10 \text{ mA}$,

$R = \frac{4.63 \text{ V}}{10 \text{ mA}} = \underline{463 \Omega}$

$V_{BB} = 4.63 + 4 \times 0.7 = 7.43 \text{ V}$

$I_{R_2} = I_{R_1} = \frac{100}{2} = 50 \mu\text{A}$

$R_2 = R_1 = \frac{700 \text{ mV}}{50 \mu\text{A}} = \underline{14 \text{ k}\Omega}$

Now, since V_{EE} changes by $2 \times -3 \text{ mV}/^\circ\text{C}$ 14
 $= -6 \text{ mV}/^\circ\text{C}$ while $V_{BE1}, V_{BE2}, V_{BE3}$

and V_{BE4} remain constant, V_{BB} changes
 by $-6 \text{ mV}/^\circ\text{C}$. But the voltage
 across the Q_3 multiplier remains constant.

Thus the voltage across the Q_2 multiplier
 should by itself so change by $-6 \text{ mV}/^\circ\text{C}$
 which can be achieved by making

$1 + \frac{R_3}{R_4} = 3$

$\Rightarrow R_3 = 2 R_4 = \underline{28 \text{ k}\Omega}$

The voltage across the Q_3 multiplier is

$V_{BB} - 3 V_{BE3} = 7.43 - 2.1 = 5.33 \text{ V}$

Thus, $5.33 = (1 + \frac{R_3}{R_4}) \times 0.7$

$\Rightarrow \frac{R_3}{R_4} = 6.61$

But $R_2 = 14 \text{ k}\Omega$, thus

$R_1 = \underline{92.6 \text{ k}\Omega}$